Australasian Tektite Geographic Pattern, Crater and Ray of Origin, and Theory of Tektite Events

DEAN R. CHAPMAN

Ames Research Center, NASA, Moffett Field, California 94035

Chemical data recently obtained on 18 major and minor elements in 507 tektites from 205 localities are used to map the geographic distribution pattern of Australasian tektites. Areas of distinct chemical type outline a coarse structure to the pattern: an elongate zone of HCa tektites stretching northwest across Australia, a crescent zone of HMg tektites curving from Australia to Indonesia to the Philippines, and a teardrop-shaped zone of normal indochinites arcing northeast over Southeast Asia. Various sets of matching polygons of specific gravity and matching chemical analyses of individual specimens define a fine structure compatible with this coarse structure. The over-all pattern is not radial, as would be required for a terrestrial origin, but is systematically curved. Numerous moon-to-earth trajectories were computed for ejecta leaving various lunar craters in a search for compatible places of origin. It was found that the complex tektite distribution pattern is matched by the trajectory landing pattern for ejecta leaving Tycho, and that the required heading direction for this ejecta coincides with one of Tycho's most prominent rays. From a study of visible elements comprising this and other similar rays, a 'connate crater' theory of tektite events is formulated which offers a reconciliation of certain tektite observations previously considered contradictory. Some implications to selenology, and comparisons with Apollo data (especially with rock 12013), are briefly discussed.

INTRODUCTION

Among four separate tektite groups presently known, the Australasian group is the youngest, most numerous, and most widely strewn. Tektites from this group have been discussed in the scientific literature for 126 years, beginning with the description of an oval australite button by *Darwin* [1844]. He suggested an origin as a volcanic bomb that burst after spinning in flight through the air (Figure 1). Subsequent evidence, however, has focused on a type of natural event much rarer than earth volcanism. Concordant age datings by the K-Ar method [*Gentner and Zähringer,* 1960] and the fission-track method [*Fleischer et al.,* 1965; *Gentner et al.,* 1967] indicate that the Australasian tektites formed in a single event about 700,000 years ago. Approximately three million of these tektites have been recovered to date at numerous localities spread from Tasmania to South China, from Thailand to the Philippines. Moreover, Australasian microtektites have been recovered in deep-sea cores from the Indian and Pacific Oceans at localities separated by as much as 10,000 km [*Glass,* 1967]. On the basis of the observed microtektite abundance, the mass of glass estimated to have fallen in this tektite event is of the order of 100 million tons [*Cassidy et al.,* 1969].

At present there is reasonable agreement as to how tektites formed, but rife contention as to where. After the discovery of metallic spherules of meteoritic Fe-Ni within phillippinites and indochinites [*Chao et al.,* 1964], and of grains of coesite in thailandites [*Walter,* 1965], it has been widely though not universally accepted that tektites originated as splash from a large meteoritic impact crater. In order to allow the small tektites to disperse over the vast distances observed, it would have been necessary, if this impact occurred on earth, for the atmosphere above the terrestrial crater to be removed. Such a removal, however, requires the order of 10^{22} erg of energy, an amount sufficient to excavate an earth crater several hundred kilometers in diameter [*Lin,* 1966; *Chapman and Gault,* 1967]. No crater this size of Australasian tektite age has yet been identified on earth. If the impact occurred on the at-

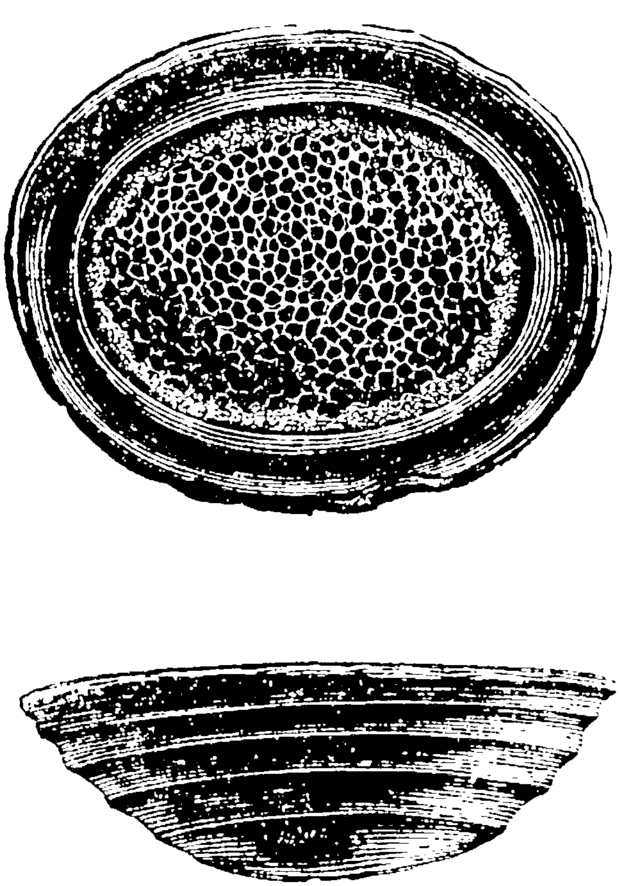


Fig. 1. First illustration known of a tektite [from *Darwin*, 1844], thought by Charles Darwin to be a volcanic bomb.

mosphereless moon, a smaller source crater, several tens of kilometers to a hundred kilometers in diameter, could account for 10^8 tons of glass on earth. Tektite form and surface sculpture have been closely reproduced in the aerodynamic laboratory, and an ablation analysis, checked by laboratory experiments, has indicated that the amount of ablation on australites is compatible with a lunar origin [*Chapman and Larson*, 1963]. A preliminary trajectory study of material originating from ten large, young, lunar craters has pointed to Tycho, in the lunar uplands, as a prime suspect [*Chapman*, 1964]. At present, however, age values for Tycho and other lunar craters are unknown; and Apollo missions have not yet returned samples from landing sites in the uplands.

The present paper is based on a 7-year program of tektite collection and chemical analysis conducted for the specific purpose of delineating the geographic distribution pattern of the Australasian strewnfield. It was hoped that from such a pattern the place of origin could be pin-pointed. During this period, more than a million tektites were inspected, about 47,000 individually measured for specific gravity, and 507 tektites from 205 different localities were chemically analyzed for major and minor elements by a single method of good precision. An additional 200 tektites were analyzed for major elements only. A summary of the chemical data, without a discussion of the geographic distribution pattern, has been presented recently [*Chapman and Scheiber*, 1969]. Complete tables of the chemical analyses are now being prepared for publication. The objective of the present paper is to present and analyze the data on earth distribution pattern of the Australasian tektites.

A fundamental thesis of this paper is that the tektite geographic distribution pattern establishes the trajectory landing pattern; and that this pattern, in turn, provides a basis for determining from where in space the shower originated. The landing pattern for earth and moon origin would differ greatly. Objects of earthly origin would travel in nearly planar trajectories for which the over-all distribution pattern, as delineated by various chemically distinct components within the shower, would form a set of radial elements, like the spokes of a wheel, projecting toward a common hub where the terrestrial crater of origin would be located. Objects of lunar origin, however, would travel to earth along nonplanar trajectories curved in three dimensions, so that their distribution on earth, owing to the combined effects of trajectory curvature and of earth rotation about an inclined axis, would form a nonradial pattern of curved elements. Such elements, together with computer calculations of moon-to-earth trajectories, would provide a means of identifying the particular lunar crater of tektite origin.

Previous evidence greatly simplifies the task of finding the place of origin. The aerodynamic ablation conditions and the initial tektite temperatures required to reproduce the common spallation-type core shapes demonstrate that before atmosphere entry the tektites were individual pieces of rigid glass. The absence of cosmic-ray exposure evidence, e.g., Al^{26}, cosmogenic neon, and cosmic-ray tracks like those present in meteorites, indicates that tektites have neither traveled far nor long in space

Reynolds, 1960; *Viste and Anders,* 1962; *Fleischer et al.,* 1965]. Hence, they came as a shower from an impact either on the moon or someplace on earth. Since only a very small percentage of glass is formed during a hypervelocity impact, it follows that the crater of genesis was large indeed. The current age of 0.7 m.y. for the Australasian shower corresponds to formation in geologically recent times. Consequently, the task reduces to one of finding a large, geologically young crater, on the earth or moon, so positioned that ejecta spurted from it would shower on earth in precisely the tektite landing pattern.

It is the design of the sections that follow, first, to outline various sysematic features in the distribution pattern of the Australasian tektites: second, to illustrate a few of many computed landing patterns of moon-to-earth trajectories that do not match this strewnfield distribution pattern; third, to document the one computed landing pattern that does match; fourth, to note some consequences to selenology that are believed to follow from the main conclusion of this paper; and finally, to sketch a theory of tektite events based on a 'connate crater' concept, which offers a resolution of certain tektite evidence that heretofore has appeared to be contradictory.

GEOGRAPHIC DISTRIBUTION PATTERN

Two assumptions underlie the present method of mapping the Australasian tektite strewnfield: (1) that the target crust material at the impact site was chemically inhomogeneous, and (2) that lunar impact ejecta upon reaching earth is highly strung out. The first assumption is based on the diverse specific gravity populations and multifarious chemical variations observed among Australasian tektites. The second assumption, as will be illustrated later, is a basic property of the mechanics of moon-to-earth trajectories. The stringing out of ejecta is also believed to be a natural consequence of the fluid dynamics of streaming material at high velocity along narrow rays from a crater. These two mechanisms acting together would tend to convert any irregular pattern of chemical variations, which may have existed within a ray as it left the moon, into an elongated or streak-like pattern by the time it reached earth.

The tektite chemical data obtained specifically for mapping the distribution pattern has revealed several distinct chemical groups and many discernible chemical types within these groups [*Chapman and Scheiber,* 1969]. A classification nomenclature evolved along two lines: some groups, like certain commercial products, were named after the chief chemical ingredient that sets them apart from the multitude (e.g., HCa, HMg, LCaHAl, HCu,B, wherein H denotes 'high' and L 'low'); other groups and types, like French wines, were named after the area from which the varietal is chiefly renowned (e.g., Dalat type, Chiang-Rai type, Serpentine Lakes type, normal indochinite, normal australite-philippinite). From recent investigations of the isotopes of oxygen [*Taylor and Epstein,* 1969] and of rubidium-strontium [*Compston and Chapman,* 1969], the distinctness of these principal groupings made on the basis of chemistry have been independently corroborated.

In attempting to map out details of the earth distribution pattern, considerable attention is given to chemical varieties that are relatively uncommon or rare. Very common types, such as the normal australites-philippinites and the normal indochinites, which are found in great numbers at many different localities across the strewnfield, presumably represent rock types that were relatively widespread at the impact site. On the basis of chemistry alone, it would be difficult to trace out within the strewnfield the landing path of tektites that are so widespread and mutually similar. Hence both specific-gravity polygons and chemistry are used to map the landing path of these common types. But the landing path of any rock mass of uncommon chemistry which happened to be at the impact site, or of any chemically unique portion of an inhomogeneous rock mass, could be readily traced out within the strewnfield simply by noting where tektites of this uncommon or unique chemistry are found. In the rest of this section, a variety of chemical characteristics are used in mapping the distribution pattern.

Coarse structure from chemical groups. The individual geographic zones for each distinct chemical group are demarked on the map of Figure 2. These zones outline a coarse structure to the distribution pattern. Prominent in Australia is an LSG-HCa 'streak,' about 300 km wide, stretching northwest for 2200 km from Tasmania to central Australia. Found only within this streak, and nowhere else in the strewnfield, are HCa populations of low modal SG (mode $\leq$2.41). Arcing from west-central Australia northwest across Indonesia, then northwest over the South China Sea, is an HMg 'crescent.' Only within this curved zone have tektites been found with HMg chemistry (the large square symbols in this zone denote HMg specimens with MgO > 3.4%, Ni $\geq$ 210 ppm, and Cr $\geq$ 210 ppm). On the fringes of this crescent, and also at some localities within this zone, are 'nearly HMg' tektites, small square symbols in Figure 2, denoting MgO > 2.8%, Ni $\geq$ 200 ppm, and Cr $\geq$ 190 ppm. Within a teardrop-shaped zone stretching northeast over Southeast Asia are the normal indochinites, with CaO/MgO = 1 $\pm$ 0.2, Ni < 35 ppm, and Cu < 5 ppm. Situated to the east, and partly overlapping the normal indochinites, is the zone of HCu, B indochinites, tektites of Muong-Nong type with Cu $\geq$ 10 ppm and B $\geq$ 30 ppm. Other chemical types for which geographic zones are not demarked, but which are identified by different symbols in Figure 2, are HAl australites (Al_2O_3 $\geq$ 14.9%) found only in eastern Australia; Chiang-Rai type (indochinites with CaO/MgO

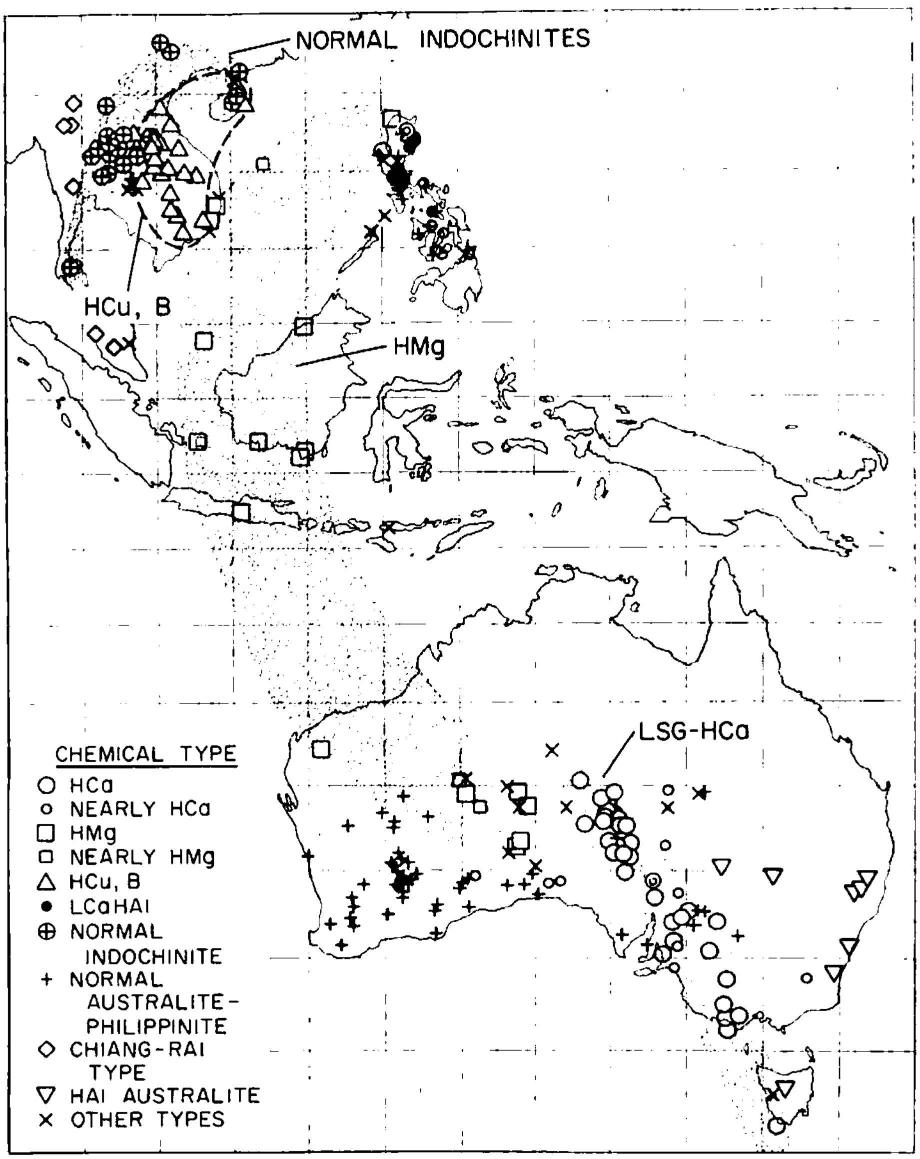


Fig. 2. Coarse structure distribution pattern of Australasian tektites as determined by zones of various chemical type.

greater than or nearly equal to unity, and with 100 < Ni < 170 ppm) found in Southeast Asia only in western Thailand and in Malaya; normal australite-philippinite (CaO > MgO and Ni ≤ 41 ppm) found essentially throughout the Philippines and southern Australia; 'nearly HCa' tektites (CaO near lower boundary of the HCa domain on a CaO versus MgO plot, and with Na_2O > 1.25% instead of Na_2O < 1.25% as in the HCa group), which are found within and near the HCa zones in Australia and the Philippines.

The principal coarse structure features in the strewnfield distribution pattern can also be demarked from the range in abundance of individual elements. Useful for this purpose is the most variable element, Ni, which ranges over a factor of 50, from 11 ppm to 615 ppm. This range is arbitrarily divided into four parts: low Ni, from 11 to 41 ppm; intermediate Ni, from 42 to 100 ppm; medium-high Ni, from 100 to 290 ppm; and high Ni, from 290 to 615 ppm. The map in Figure 3 shows the regional distribution of Ni abundance. It is seen that low Ni tektites are found throughout the strewnfield, in Australia, Southeast Asia, and the Philippines. Hence, low Ni does not define a distinct pattern. This circumstance arises because several different chemical types each are low in Ni (e.g., HCa group, LCaHAl group, normal indochinites, and normal australite-philippinites). The high Ni tektites, however, are found only in the HMg group, and demark the same crescent zone as that demarked by the HMg tektites. High values of Co and Cr provide still another independent method of delineating precisely the same crescent.

As another example, tektites that are both uncommonly low in Ni (below about 25 ppm Ni) and high in silica (above about 77% SiO_2) define two different geographic zones: one that is the same as the LSG-HCa streak in Australia, and another that is the same as the HCu,B zone of Muong-Nong type tektites in Southeast Asia. Australasian tektites both low in Ni and high in SiO_2 have not been found elsewhere.

Still another independent source of data that is most helpful in defining the distribution pattern is provided by measurements of specific gravity. Such measurements were made on about 47,000 individual tektites of the normal, nonspongy variety. A wide variety of SG polygons was found, as is illustrated in Figure 4. Some populations are very homogeneous (Wiang Papao, Figure 4*c*, others are heterogeneous (Sangiran II, Figure 4*b*); some are bimodal (Figure 4*a*), other trimodal or even quadrimodal. These variations in SG polygon correlate well with chemical variations: HMg chemical populations have heterogeneous SG polygons always with high-SG specimens above 2.47 (Figure 4*b*); normal australite-philippinites, in contrast, have relatively homogeneous SG polygons without specimens above 2.47 (Figure 4*d*); while HCa populations are distinguished by bimodal or multimodal SG polygons (Figure 4*a*). Population polygons with low modal SG, less than 2.42+, are found only in two zones: within the LSG-HCa streak in Australia, and within the normal indochinite zone in Southeast Asia. Apart from a few obvious exceptions, an SG polygon reflects closely the true material SG polygon rather than variations in bubble content [*Scheiber*, 1970]. Inasmuch as SG varies inversely with SiO_2, it follows that an SG population polygon for a given locality represents the spectrum of SiO_2 variation. Hence it should not be surprising that the coarse structure pattern of chemical variations and the SG data are mutually consistent.

Several early attempts to define a geometric pattern within the strewnfield distribution of Australasian tektites each have led to patterns different from that constructed herein. As is explained in Appendix 1, these differences are attributed to the relatively meager quantity of data available in earlier investigations.

Fine structure from SG-polygon matches and chemical matches. Four separate conditions are employed to define additional detail within the strewnfield pattern. Fine structure is delineated by tracing loci of 'matching' localities. The criterion selected for a match depends upon how common or rare is a given chemical type. For a match between localities of the very common types (e.g., normal australites-philippinites, normal indochinites, Dalat-type indochinites), it was required that either (1) SG polygons match for the same type of tektite chemistry or (2) chemical analyses match for the same type of SG polygon having the same modal SG. For less common types (e.g., HCa,

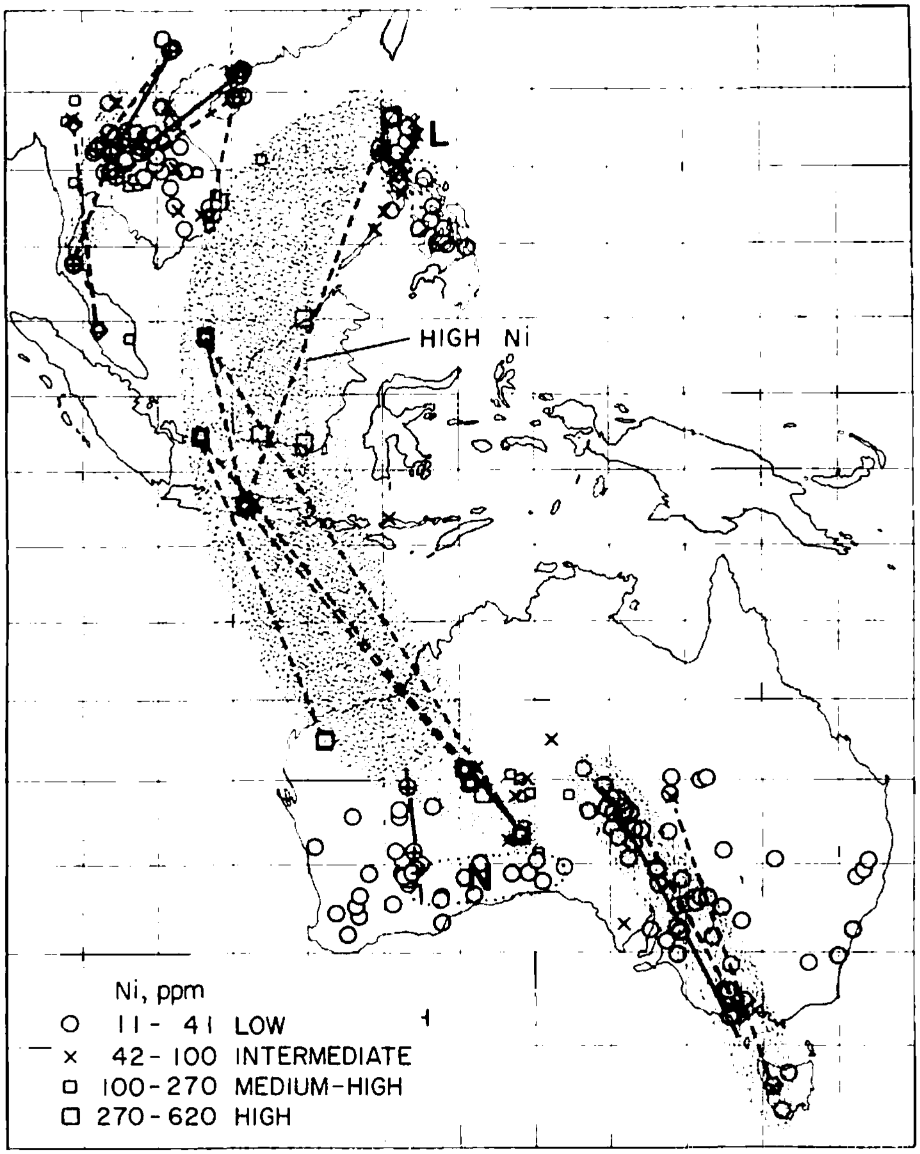


Fig. 3. Distribution pattern of Australasian tektites as determined by Ni abundance.

HMg, HCu,B, Serpentine Lakes type), it was required that (3) chemical analyses match for the same type of SG polygon having the same modal SG to within 0.01. For the uncommon or rare types (e.g., Sangiran II, which combines HMg with SG > 2.5), it was required only that (4) chemical analyses match. The first two matching conditions, which are applied to very common types, are envisioned as trailing the splash from a part of a rock mass that was relatively widespread at the impact site. Match condition 4, in contrast, is envisioned as trailing smaller masses of rarer composition, or of unique chemistry, that happened to be swept into the fused ejecta as it streamed from the source crater.

It is emphasized that the identification of strewnfield fine structure for all but the rare or uncommon chemical varieties involves consideration of *both* the chemistry of individual specimens and the polygons of specific gravity. Various examples illustrating the importance of considering both chemistry and SG polygons are presented in Appendix 2.

Inasmuch as a broad spectrum of SG polygons is observed within the strewnfield (Figure 4), a match between populations from two or more different localities is significant. Six sets of matching SG populations are shown in Figure 5. Elementary computations of probability indicate that the chance of accidentally reproducing two population polygons that match to this degree over their entire spectrum of SG is of the order of one in a thousand. Each match illustrated is for the same type of tektite chemistry. From left to right in Figure 5*a*, the four-locality match is for the low-SG mode of HCa populations found along the LSG-HCa streak in Australia; the match of Pia Oac (North Vietnam) and Kasetsomboon (Thailand) is for normal indochinites; and the match of Ooldea (South Australia) and Coco Grove (Luzon) is for the normal australite-philippinite type. In Figure 5*b* the match of Kuchinari (Thailand) and Fort Bayard (South China) is for normal indochinites; that of West Kalgoorlie (West Australia) and Kubao (Manila) is for the normal australite-philippinite type, as is the three-locality match of Boyce Creek, Lake Lapage, and Earaheedy (all in West Australia). Since both Ooldea and Kalgoorlie are from the Nullabor Plains of Australia, and both Kubao and Coco Grove are from Luzon, these two matches are referred to subsequently as the Nullarbor-Luzon match. Such a match has been observed previously [*Chapman et al.*, 1964]. In Figure 6 the Nullarbor area is designated by the encircled *N*, the matching Luzon area by an *L*. Other localities of matching SG polygons are shown connected together by solid lines in this figure.

A computer was used to search for all possible matching analyses within the chemical data. The 507 tektite analyses for 18 major and minor elements were digitized on punch cards. Altogether about 125,000 different combinations of pairs of tektite analyses were then tested by the computer for possible chemical matches. The quantitative criteria used for a match were based on the experimental precision of determining a given element. The mean deviation σ between replicate determinations of that element from a given sample of tektite powder was taken as a measure of the precision. For a chemical match it was required that all major elements with at most one exception be the same within 2σ, that the one excepted major element (if any) be the same within $\pm 2\sigma$, that all minor elements with at most one exception likewise be the same within 2σ, and that the one excepted minor element (if any) be the same within $\pm 2\sigma$. The 2σ precision was taken as 6% for Mg, Na, Al; 7% for Ca, K, Fe; 20% for Ti, Ni, Mn, V; 25% for Ba, Co, Cr, Y, Zr; and 30% for B,Cu. The 2σ precision for silicon, which was determined by

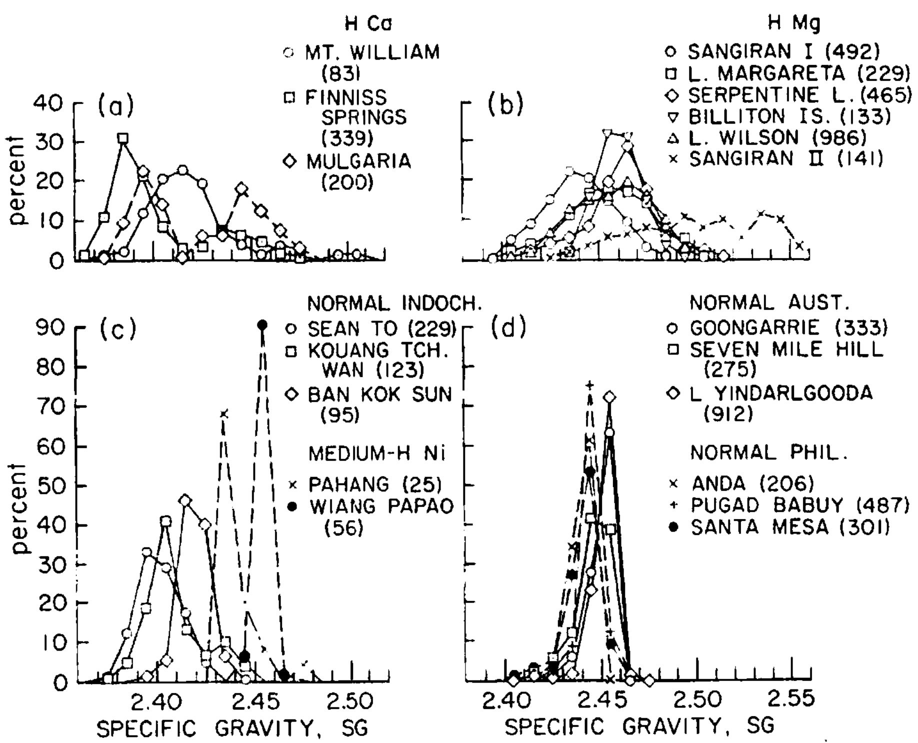


Fig. 4. Specific-gravity population polygons for various chemical types: (*a*) HCa australites, (*b*) HMg tektites, (*c*) normal indochinites and localities with medium-high Ni, (*d*) normal australites and normal philippinites.

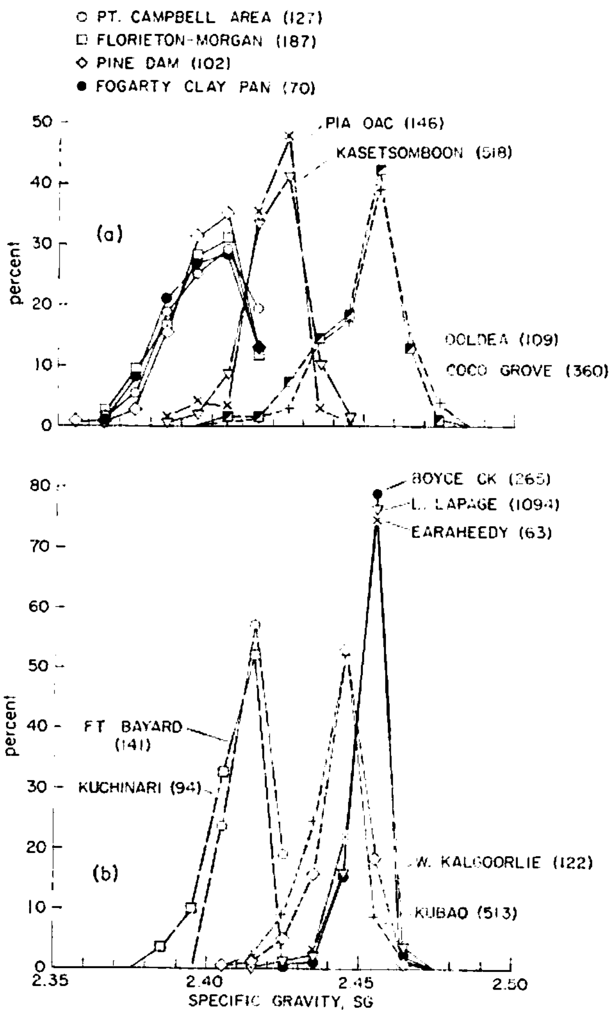


Fig. 5. Six sets of matching polygons of specific gravity: (*a*) left to right, matches along LSG-HCa australite streak, North Vietnam-Thailand match, and Nullarbor Plains-Luzon match; (*b*) left to right, South China-Thailand match, West Australia-Luzon match, and West Australia matches.

difference from the total of the other elements, was taken as 1.5%. In a few cases where an element was uncommonly low in abundance, the 2σ precision was taken as an appropriate increment rather than as a percentage.

Not all matching analyses identified by the computer, nor all locality pairs at which the SG polygons match, can be considered a significant feature of the original shower pattern. Obviously, a match between two localities only several tens of kilometers apart may reflect some geological transport process rather than a characteristic of the tektite trajectory landing pattern. Also, locality data for some specimens are uncertain by as much as 50 km. More important, the elongate zone of a given type is at least several hundred kilometers across. Consequently, only those locality pairs of chemical matches separated more than about 1000 km would provide relevant evidence on the 'streak paths' within the over-all trajectory landing pattern.

Various examples of matching analyses as determined by the computer search are presented in Table 1. These include matches between normal australites and philippinites (matches 1 and 2), between Dalat type tektites (match 3), between normal indochinites (match 4, a tri-locality match), between HMg tektites (matches 5, 6, 7), between other less common types (matches 8, 9), and between rare types (matches 10, 11). In Figure 6 the locality pairs for matching analyses are shown connected together by dashed lines. It is evident from this figure that the fine structure, as represented by these lines of matching chemistry, is quite consistent with the coarse structure (shaded zones) and with the fine structure of matching SG polygons (solid lines).

Directional conditions and relative temperature of formation. In comparison to australites, the internal flow structures of tektites from Southeast Asia are indicative of formation in a much more viscous condition. Within indochinites, the lechaterlierite inclusions appear less softened and contorted, the internal bubbles are commonly elongate instead of spherical as in australites, and minute grains of unfused minerals are found [*Barnes*, 1963*a*, *b*; *Glass*, 1970]. Moreover, their external shapes are larger and much more irregular than australites. All these are signs that the indochinites formed at a higher viscosity than the australites. Higher viscosity implies lower temperature, a lower internal energy increase ΔE, and a lower particle velocity V_p of shock acceleration ($\Delta E = (1/2)V_p^2$ according to the Rankine-Hugoniot conservation equations for strong shock waves). The irregularly shaped tektites from Southeast Asia, therefore, were ejected from their crater of origin at a lower velocity than were the australites. This condition of decreasing ejection velocity in the direction from Australia to Thailand is an important directional condition to be imposed on the trajectory landing pattern of the Australasian tektite shower.

From study of the geographical variation of tektite shapes and sizes within a given chemical group, a number of other directional conditions have been deduced. Within the low-SG component population along the LSG-HCa streak, for example, the average size of substantially whole tektites (all but the broken ones) increases systematically in the northwest direction, varying from about 2 grams in Victoria to 2.6 grams at Florieton, 4 grams in the area of Mulgaria-Witchelina-Pine Dam, about 6 grams at Charlotte Waters, and about 10 grams at Henbury. Also, 100% of the cores in Victoria have a smoothly curved base, whereas about 1/3 of the cores at Charlotte Waters have bases that are irregularly curved. Clearly, the direction of increasing viscosity of formation, and hence of decreasing velocity of ejection, runs northwest from Victoria to Henbury. Another example is provided by the HMg javanites and australites. The billitonites, averaging 19 grams, and the javanites (Sangiran I with 2.38 < SG < 2.48) are considerably larger and more irregularly shaped than the HMg australites of similar SG range. This indicates a decreasing velocity of ejection in the direction running NNW from the HMg area in Australia to Sangiran in Java. Still another example of a directional condition is provided by the indochinites at Pia Oac in North Vietnam and at Kuchinari in northeast Thailand, which have matching SG polygons: the Pia Oac tektites average about 30 grams versus about

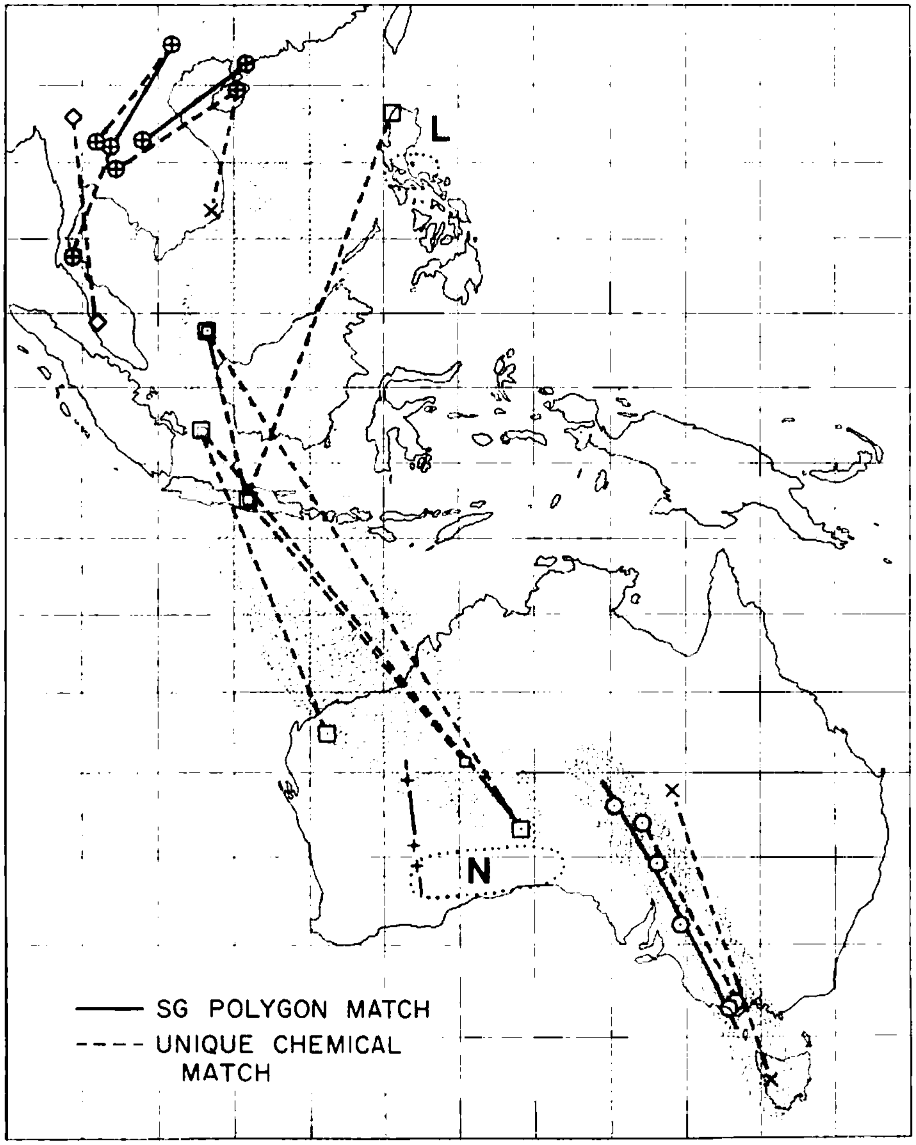


Fig. 6. Fine structure distribution pattern of Australasian tektites as determined by matching chemical analyses and matching polygons of specific gravity.

TABLE 1. Examples of Matching Chemical Analyses
(Oxides in weight per cent, elements in parts per million.)

	Match 1		Match 2		Match 3		Match 4			Match 5		Match 6	
	P420 Bato-balani C. Grove	AN58 27 mi. so. of Cook	AN315 Yandal	P314M Kubau	1125 H. Suoi Vang, Dalat	SCH22 Kouang Tcheou Wan	T241 Surat Thani	T254 Ban Kok Sun	1110 Pia Oac	AN59 Giles Creek	J83 Sangi-ran Java	AN226 Ser-pentine Lake	BN5 Billiton Is.
SG	2.435+	2.445+	2.455		2.410+	2.425+	2.420+	2.400+	2.426	2.445+	2.467	2.477	2.486
RI	1.509	1.515	1.513	1.513	1.504	1.507	1.507	1.506	1.506	1.515	1.518	1.516	1.519
SiO_2	72.5	72.1	70.7	71.6	74.2	73.3	73.1	73.4	72.6	73.9	72.1	70.5	71.0
Al_2O_3	12.8	12.9	13.4	13.0	12.9	12.7	13.3	13.1	13.8	11.2	11.9	12.4	11.7
FeO	4.52	4.71	4.96	4.55	4.77	4.89	4.66	4.56	4.60	5.50	5.65	5.66	6.04
MgO	2.15	2.15	2.30	2.42	2.24	2.35	2.00	1.97	1.99	3.42	3.49	3.42	3.61
CaO	2.71	2.89	3.36	3.31	1.94	2.02	2.22	2.18	2.37	2.82	2.71	3.21	3.16
Na_2O	1.54	1.50	1.58	1.50	1.31	1.36	1.23	1.31	1.17	1.09	1.07	1.42	1.30
K_2O	2.61	2.53	2.54	2.47	2.47	2.45	2.36	2.39	2.39	2.00	2.03	2.25	2.12
TiO_2	.75	.82	.73	.78	.72	.75	.76	.67	.73	.61	.68	.78	.67
B	19	20	22	39	31	27	11	13	18	22	20	23	28
Ba	440	430	440	400	350	340	305	445	380	315	400	360	380
Co	12	14	16	13	18	20	11	11	12	33	33	37	36
Cr	78	100	92	105	120	130	58	61	56	265	240	225	280
Cu	4	5	6	8	5	4	<4	<4	<4	5	5	5	6
Mn	800	780	700	670	800	920	735	740	880	760	790	825	830
Ni	27	29	31	25	100	110	16	15	15	250	290	295	370
V	89	89	87	87	65	71	63	63	65	65	73	66	70
Y	33	30	27	32	26	28	30	27	29	26	32	29	27
Zr	240	270	280	270	280	290	300	300	290	245	280	280	280

	Match 7			Match 8		Match 9		Match 10		Match 11	
	AN122 near Young Range	J71 Sangi-ran Java	NAI1 Natuna Is.	T237 Ban Mae Jong	MYH1 Batu Gajah Malay	AN348 Mort-Lake	AN259 E. of Div. Bluff	AN254 Mount Darwin Tas.	AN198 Alton Downs	P192 Pasuquin Luzon	J59 Sangi-ran Java
SG	2.455+	2.457	2.455	2.443+	2.442	2.375+	2.380+	2.390+	2.385	2.507	2.511
RI	1.514	1.513	1.512	1.511	1.511	1.496	1.497	1.500	1.497	1.525	1.527
SiO_2	71.7	72.0	71.9	72.7	72.9	78.1	77.9	76.8	76.8	69.4	69.6
Al_2O_3	12.5	12.0	12.2	12.5	12.3	10.5	10.4	11.6	11.7	12.3	12.2
FeO	5.20	5.32	5.41	4.85	4.74	3.69	3.90	3.97	3.92	6.70	6.94
MgO	2.99	3.19	3.04	2.41	2.59	1.46	1.52	1.59	1.53	5.01	5.06
CaO	2.84	2.85	2.54	2.79	2.73	2.01	2.08	1.75	1.72	2.78	2.72
Na_2O	1.36	1.31	1.40	1.33	1.28	1.10	1.16	1.04	1.07	.88	.75
K_2O	2.34	2.26	2.42	2.31	2.29	2.22	2.16	2.12	2.18	1.75	1.67
TiO_2	.72	.68	.68	.75	.73	.58	.53	.73	.66	.76	.68
B	26	34	44	19	20	16	22	20	26	35	16
Ba	380	370	400	440	395	410	360	400	425	400	490
Co	31	26	27	18	23	9	10	9	10	41	40
Cr	210	210	195	120	140	54	59	76	59	310	300
Cu	5	5	6	5	4	5	<4	<4	<4	4	4
Mn	840	840	805	830	900	610	610	690	680	990	900
Ni	230	200	215	120	165	16	17	21	20	325	300
V	73	64	80	76	69	46	54	46	45	62	63
Y	26	24	30	29	29	31	28	27	24	29	27
Zr	260	260	290	310	305	350	290	310	320	315	265

19 grams in northeast Thailand. In this case the direction of decreasing velocity of ejection (increasing size) runs northeast. At three different localities in northern Luzon where tektites of intermediate Ni content are found (42 ppm $\leq$ Ni $\leq$ 53 ppm), the average weight is between 6 and 14 grams, whereas it is a little less than 6 grams at Busuanga in the southwest Philippines. In this case the inferred direction of decreasing ejection velocity is NNE. The Sangiran II tektites of high SG average less than 1 gm weight; and, among 141 examined, the largest weighed 6.1 grams, whereas all the rest weighed less than 2.6 grams. In contrast, the tektite with a matching analysis in northern Luzon (P192, match 11 in Table 1) weighs 8.3 grams. Hence this inferred direction of decreasing ejection velocity is from Java NNE to the Philippines.

Composite distribution pattern. Assembled in Figure 7 is a composite map showing the localities of microtektites, the zones of various chemical type, the lines of fine structure, and arrows indicating the directional condition of decreasing ejection velocity (V_E). This map summarizes the principal elements known about the earth landing pattern of the Australasian tektite shower. That the pattern is nonradial, without a center of emanation, is evidence that the shower was not of terrestrial origin. In essence, Figure 7 provides a rough Rosetta stone for deducing from which lunar crater the tektites came.

Determination of Origin

The method used to determine which lunar crater could have distributed ejecta on earth in the particular pattern of the tektites is the time-honored method of trial and error. Evidence that the source crater was both large and geologically young greatly limits the number of trial craters; the fact that the moon presents substantially the same face toward earth greatly limits the variety of distribution patterns for a given crater. For each trial crater, a determination was made first of the azimuthal heading direction δ (measured in degrees north of lunar east) required to launch material toward earth, then of the elevational angle β (measured from the local lunar zenith) required to hit the Australasian part of the globe. Numerous moon-to-earth trajectories were computed for a 2° spread in both δ and β, and for the complete range of lunar ejection velocity V_E that sends material directly to earth. These computed patterns and the tektite distribution pattern were then compared.

The computer program used in the present calculations of moon-to-earth trajectories is a much refined version of a program used earlier [*Chapman*, 1964]. In this previous work the lunar equator and the lunar orbit plane were assumed to coincide with the ecliptic plane, and the lunar orbit was taken to be circular. The present program takes into account the 5°9′ mean inclination of the lunar orbit plane to the ecliptic, the 1°32′ angle between the lunar equator and the ecliptic, the elliptical orbit of the moon, and the librations in latitude and longitude as prescribed by the laws of Cassini. It also takes into account the regression of nodes, the advance of apsides, as well as

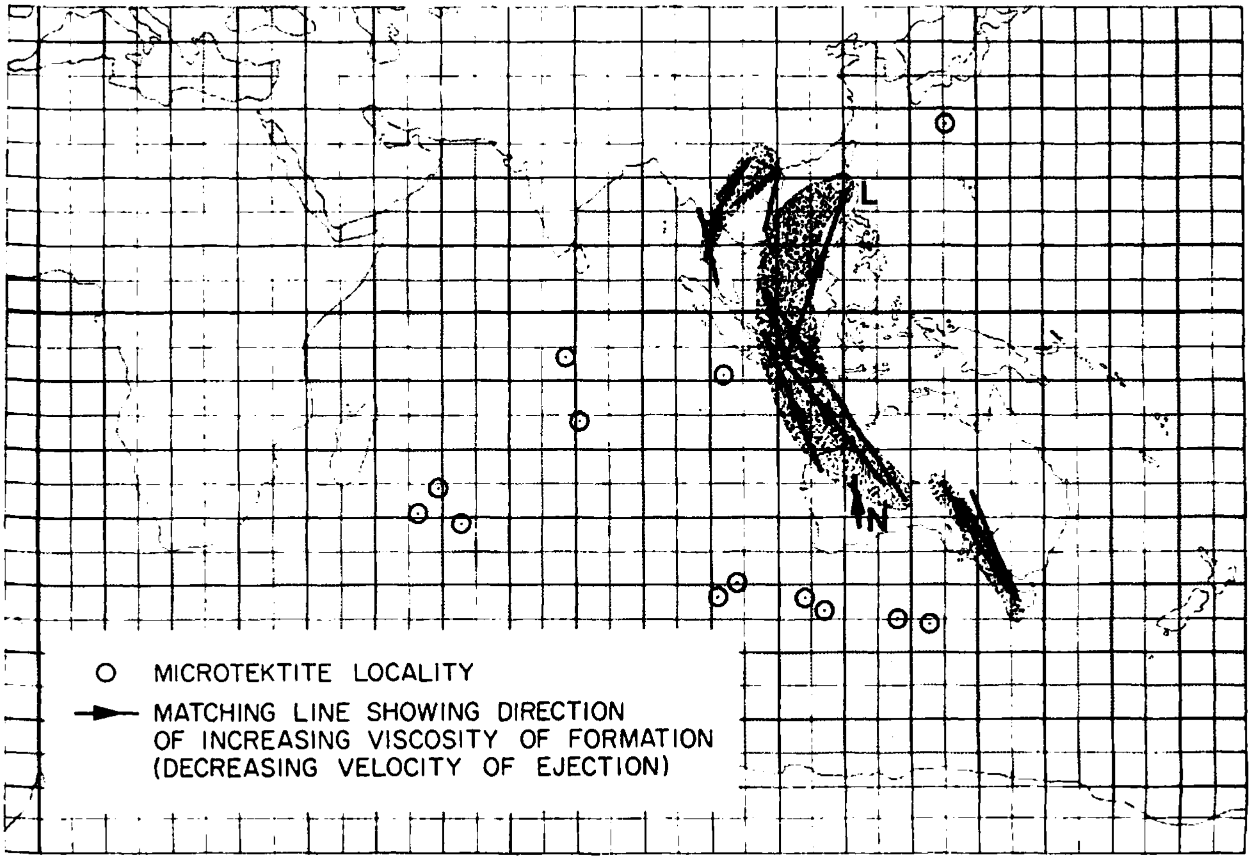


Fig. 7. Australasian tektite distribution pattern: Microtektite distribution and principal features of distribution pattern for land tektites.

perturbations of the sun according to an approximate theory worked out by Dr. William Mersman. In order to obtain a check on accuracy, seven test cases were run both on the present program and on the Apollo program of the Real Time Computer Complex at the Manned Spacecraft Center, Houston. The agreement in all cases was satisfactory.

As was noted above, a 2° spread in both azimuth (δ) and zenith (β) angle at lunar ejection was used for most calculations. An azimuthal dispersion $\Delta\delta = 2°$ was selected from observations of the width of lunar rays. Most rays are less than 2° wide. An equal elevational dispersion $\Delta\beta = 2°$ was selected partly on the basis of a theoretical interpretation (described later in this paper) of the mechanism by which lunar ray elements are ejected from their parent crater. The laboratory impact experiments of *Gault et al.* [1962] would suggest that a value somewhat larger than $\Delta\beta = 2°$ might be more appropriate. For the relatively narrow range in velocity of 2.5 to 2.9 km/sec, which represents the velocity range for 90% of the material that can hit the earth from the moon, these laboratory experiments would suggest values for $\Delta\beta$ up to about 3° or 4°. Consequently, in order to investigate what effect a greater elevational dispersion would have, some landing patterns were computed for $\Delta\beta = 4°$ (these are illustrated later). In order to investigate what effect a smaller dispersion would have, such as is observed for some ray elements, landing patterns were computed for a dispersion $\Delta\beta = \Delta\delta = 1°$ (also illustrated later).

The earth distribution patterns for each trial crater were found to depend chiefly on the lunar celestial longitude at the time of lunar ejection. Only weak dependence was found on such parameters as libration angles, sun position, and the moon's position relative to perigee. Increments in lunar longitude were taken small enough to safely interpolate between computed patterns. No two patterns were the same for different craters. Thus each crater can be characterized by a unique set of earth landing patterns, analogous to a set of fingerprints, any one of which may serve for the purpose of identification.

From the family of trajectory landing patterns for a given crater, the only pattern illustrated herein is the one judged as coming closest to meeting the basic requirement of spreading ejecta across at least the 74° range in earth latitude (from 46°S to 28°N) presently known for Australasian tektites. Among the many trial craters that failed to match the tektite strewnfield pattern, only a few will be mentioned. Throughout the illustrations, the direction of decreasing lunar ejection velocity V_E is indicated on the earth trail lines by an arrow. Each trail line represents constant values of δ and β, and variable values of V_E ranging over the full spectrum from the highest down to the lowest velocity that will land material on earth.

Landing patterns for three trial craters are shown in Figure 8. Strabo, situated in the northern hemisphere of the moon's near side, meets the requirement of spreading material over a 74° latitude range, but is incompatible with the tektite streak pattern, and with the directional requirement of V_E decreasing *northward* (Figure 8*a*). Strabo clearly provides no match for the tektite distribution. Another example of a trial crater that failed, as Figure 8*b* shows, is one situated on the moon's far side (latitude 10°N, longitude 118°E). As V_E decreases, material from this crater would sweep eastward. Other craters on the far side are similarly incompatible because of their generally eastward trails on earth. Still another example of a crater that failed is Copernicus (Figure 8*c*). In this case the latitude spread is comparable to that of the Australasian strewnfield, but the looped pattern does not match that of the tektites.

It would be pointless to document further various trial craters that failed. Six years ago, when relatively little was known about the earth landing pattern of the tektites, a number of moon-to-earth trajectories were investigated for 10 large, young, lunar craters. It was found that of these only Tycho was so situated as to be able both to spread ejecta generally northward as V_E decreased, and to spread it over the required latitude range [*Chapman*, 1964]. Two years ago, when the present chemical data were partially complete, Tycho still appeared to be the prime suspect [*Chapman*, 1968]. With many details of the landing pattern now delineated, this prime suspect can be put to a severe test.

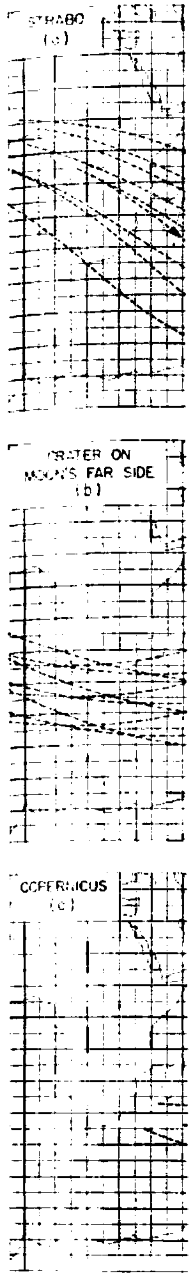


Fig. 8. Thre
landing pattern
the observed t

Figure 9 ill
for ejecta fron
the lunar long
267°, conform
pattern in al
longitude spre
gascar to sout
sponding spre
the Tycho pa
across Austra
closely oriente

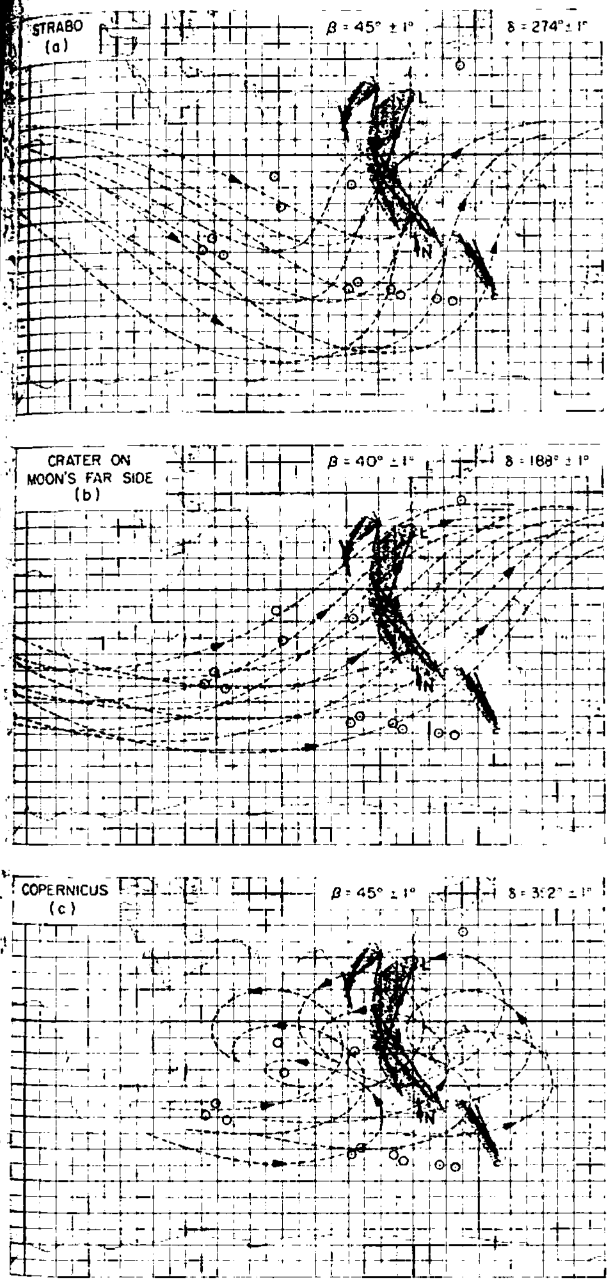


Fig. 8. Three representative examples of earth landing patterns for craters that failed to match the observed tektite distribution pattern.

Figure 9 illustrates an earth landing pattern for ejecta from Tycho. This pattern, for which the lunar longitude at the time of ejection was 267°, conforms with the tektite distribution pattern in all essential details. The over-all longitude spread of tektites from near Madagascar to south of Japan, as well as the corresponding spread in latitude, is compatible with the Tycho pattern; the northwesterly streak across Australia of the HCa australites is closely oriented with trail 4 of the Tycho pattern; the line of chemical match between Tasmania (Mount Darwin) and Central Australia (Alton Downs) virtually coincides with trail 4; the nearly northern streak in Western Australia, of normal australites with matching polygons of specific gravity, conforms with a trail interpolated between trails 8 and 9; the curved crescent zone of the HMg tektites is compatible with the curvature and positions of trails 1 and 5; the various streak lines of chemical matches within the HMg zone are also either in reasonable or in very close agreement with trails 1 and 5; the northeasterly streak lines across Southeast Asia are compatible with trails 2, 5, and 9; the nearly north streak from Malaya to West Thailand is parallel to, and just west of, trail 9 (interpolate between trails 9 and 6); the Nullarbor Plains match with normal philippinites in Luzon (N to L in Figure 9) falls along trail 1; and the various directional conditions for decreasing V_B, as designated by arrows, conform with the Tycho pattern at all areas of the strewnfield for which these conditions have been deduced from the tektite data. The chance that these many coincidences are merely accidental would represent an improbability of epic proportions.

This, however, is not the total evidence. As is noted in the upper right of Figure 9, the matching pattern represents material ejected from Tycho in one particular heading direction, namely, δ near E 19°N; and at one zenith angle, namely, β near 52°. A zenith angle of $\beta = 52°$, corresponding to ejecta leaving 38° from the lunar horizontal, is indeed a very reasonable angle for hypervelocity impact ejecta. A more crucial test, however, is whether or not a ray from Tycho was shot in the particular heading direction of $\delta = 19°$. In Figure 10 the great-circle direction represented by $\delta = 19°$ is designated by a short white line extending about three crater diameters from Tycho, and by the large arrow representing its continuation near the eastern limb of the moon. The heading E19°N from Tycho is seen to coincide, in fact, with one of the most prominent rays of Tycho, the 'Rosse ray,' which streams across the Sea of Mare Nectaris over the small crater Rosse in this sea. That the Australasian tektites came from the Rosse ray of Tycho is, in this writer's view, an inescapable conclusion.

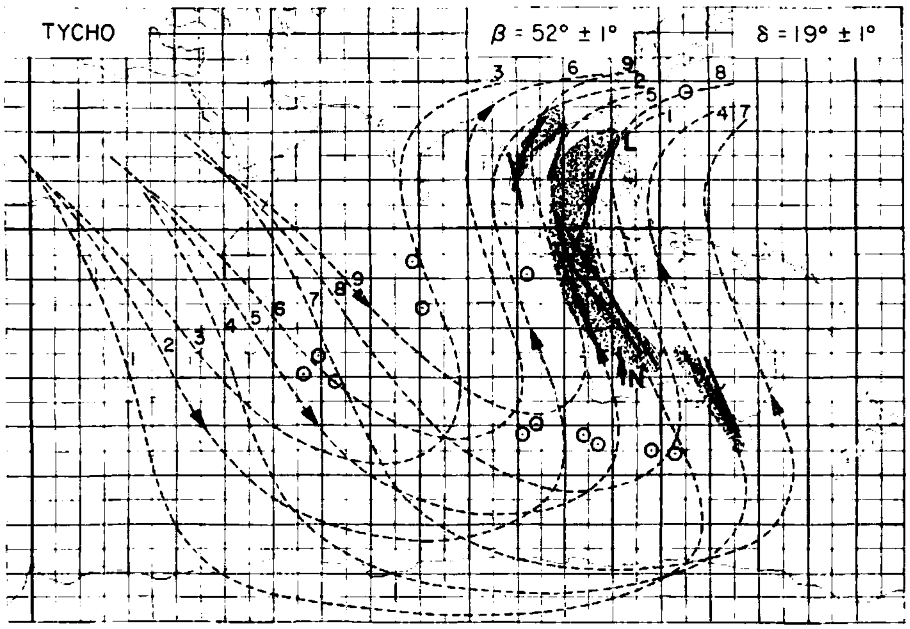


Fig. 9. Matching of earth landing pattern from Tycho with observed tektite distribution pattern.

CONNATE CRATER THEORY OF TEKTITE EVENTS

Certain evidence from tektite groups other than Australasian has led some to the conclusion that tektites originate from earth rather than moon craters. Current age data from both K-Ar and fission-track methods indicate that two craters on earth may have formed simultaneously with two tektite showers: the Ries crater in Germany simultaneously with the Czechoslovakian tektites about 15 m.y. ago, and the Bosumtwi crater in Ghana simultaneously with the Ivory Coast tektites about 1 m.y. ago [*Gentner et al.*, 1964, 1967, 1970; *Fleischer et al.*, 1965]. It is to be noted, however, that such an inference of a terrestrial origin for these tektites, which conflicts with the aerodynamic and trajectory evidence of a lunar origin for the Australasian tektites, is not the only possible inference which can be drawn from the age data.

It might be thought, for example, that the moldavites and Ivory Coast tektites are from the earth, while the Australasianites are from the moon. But, so extraordinary are the similarities in physical makeup of all tektites that this compromise interpretation seems untenable. Also, rocks having the same major and minor element composition as Ivory Coast tektites have not been found at Bosumtwi; likewise, rocks of moldavite composition have not been found at Ries. More devastating to the idea of a terrestrial origin for Ivory Coast tektites is the recent discovery of Ivory Coast microtektites in deep-sea sediments about 1300 km from Bosumtwi [*Glass*, 1968, 1969]. This distance is much too short to have produced any ablation droplets of tektite glass, yet is much too far for these objects (the largest are nearly 1 mm in size) to have traveled through the earth's atmosphere either by winds or by ballistic trajectories: and Bosumtwi crater is much too small to have temporarily removed the earth's atmosphere.

Still a different interpretation is that large, crater-forming objects impacted the earth simultaneously with the tektites. This broad possibility was noted, though without elaboration, by *Fleischer et al.* [1965]. A specific model advocated by *von Koenigswald* [1967] pictures both the earth and moon as having simultaneously encountered a swarm of large meteorites, some of which struck the moon and created tektites that later landed on earth, while others struck the earth and formed contemporaneous craters accidently near the tektites.

An alternate model compatible with both age and aerodynamic data is advanced herein. A tektite event is envisioned as originating from a burst of composite ejecta spewn from a meteoritic impact on the moon, ejecta comprising myriads of tektites together with one or more large fragments of the original meteoritic projectile. When this ejecta mélange lands on earth, each large fragment would excavate a terrestrial crater 'connate' with, but not a parent of, the tektites. At first it would seem difficult to explain by this hypothesis how objects as large as those that excavated the Ries and the Bosumtwi craters could be thrown as fragments from a lunar crater. Around Arizona crater, iron meteorite fragments were found weighing of order 10^{-1} of the estimated mass of the original impacting meteorite. In order to form earth craters the size of Bosumtwi and Ries from a meteoritic fragment of mass 10^{-1} of that which struck the moon, the lunar-impacting meteorite would have to be of such size as would excavate a lunar crater roughly 50 to 100 km across. Consequently, tektite events forming connate earth craters the size of Bosumtwi or Ries can come only from large lunar craters, and therefore can occur only infrequently. Thus the 14 m.y. separating Ivory Coast and Czechoslovakian tektites, and the size of Bosumtwi and Ries craters, appear compatible with the connate crater idea.

In essence, the concept of connate craters inverts an apparently obvious association: it implies strangely that tektites are not on earth because certain large craters of identical age are, but vice versa. Past examples of inversion theories, which twist around seemingly evident causal associations, sometimes have succeeded eminently. The sun's apparent revolution daily around the earth, for example, is explained by the earth revolving, rather than the sun. The apparent creation of swarms of infusoria and bacteria seemingly out of nowhere from decaying matter is also explained by an inversion: by bacterial life causing decay, rather than decay creating life. Analogously, the present theory of tektite events associating a large entity causatively with a multitude of tiny objects attributes the existence of the large to the associated swarm of small forms, rather than the other way around.

A connate crater model for tektite events is constructed herein on the basis of a certain

Fig. 10. Source crater and ray of Australasian tektite origin.

interpretation of the visible structure of lunar rays. Telescope observations reveal that a lunar ray is not continuous, but is generally composed of a series of many elongate 'ray elements' [*Pickering*, 1892; *Kuiper*, 1965], each closely aligned with the main ray. These elements commonly resemble an exclamation mark (!), the linear streak appearing to spray radially outward from either a 'craterlet' or a cluster of craterlets. These craterlets are clearly secondary craters made by ejecta from the large primary crater. Near the primary crater, ray elements are superimposed so densely upon one another that a ray there appears virtually continuous. Farther out the ray elements become clearly separated. Figure 11 illustrates two such elements: one, comprising the craterlet Rosse and its associated 'spray,' is part of the prominent ray from Tycho that is associated herein with Australasian tektites; the other, comprising Messier A crater and its associated spray, is possibly part of a ray system from a crater situated on the moon's far side. *Whitaker* [1965] states that the Messier spray is precisely radial to an unnamed ray center photographed by Lunik 3 on the back side of the moon. *Billerbeck-Gentz* [1943] has emphasized that the Rosse ray element appears to be just one of four mutually associated elements aligned nearly end to end. An adaptation of his sketch is presented in Figure 12. The scale can be judged from the diameter of Rosse (~13 km) and the visible length of its associated spray (~220 km). These four ray elements are interpreted herein as the result of four large objects of crater-forming size being hurled from Tycho in nearly the same azimuthal direction, shock-accelerated and shock-heated crust being sprayed around and ahead of each object as it left Tycho.

The 'craterlet' Rosse is itself a large crater. Its size, 13 km in diameter, implies that ray elements can include very large objects. Situated approximately 1450 km from Tycho, it would have been excavated by a secondary object impacting at about 1.3 km/sec. If that same object were hurled to earth, however, it would impact at 11 km/sec, a much greater velocity, because of the earth's gravitational attraction. According to crater scaling laws, an earth impact of the Rosse object would excavate a terrestrial crater of diameter approximately 30 km. Thus, earth craters as large as Ries (24 km), or Bosumtwi (11 km), appear well within the possible size realm for craters originating as connates to a tektite strewnfield of lunar origin.

The large objects that trail a ray element upon ejection from a primary crater must be either blocks of lunar crust or fragments of the

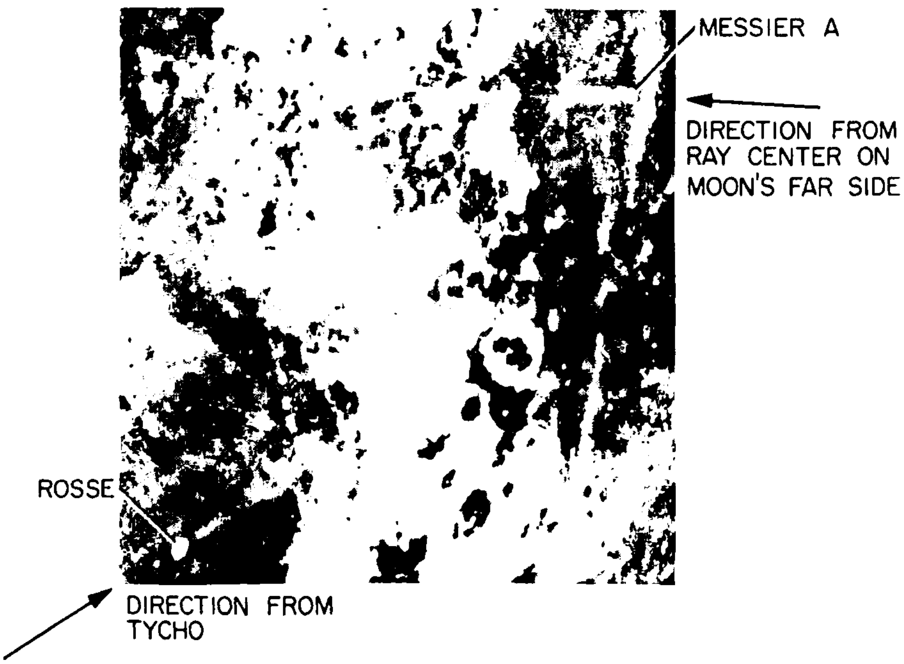


Fig. 11. Lunar ray elements Rosse and Messier.

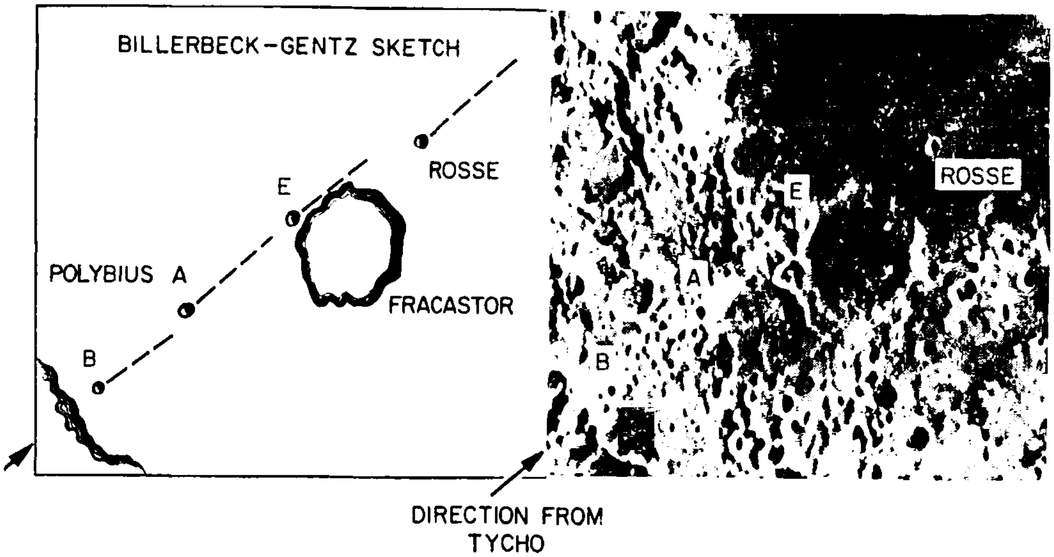


Fig. 12. Four nearly linearly aligned ray elements along Rosse ray of Tycho.

original cosmic projectile. Around the Arizona crater, large sandstone blocks are observed only relatively near the crater, not far out. The fragments of iron meteorite, in contrast, are observed out to much greater distances (~7 km) such as would imply, according to the equations of ballistic flight in the earth's atmosphere, a velocity of ejection of several kilometers per second (a velocity sufficient to escape the moon). A large projectile fragment can be ejected from a crater with greater velocity than a large crustal block, since a block of target crust must be accelerated from rest to its launch velocity, whereas a fragment of projectile need only be redirected, particularly in an oblique impact. Tycho appears to have been an oblique impact: its asymmetric splash pattern indicates an approach of the impacting body along virtually the same direction as that of the Rosse ray which contains the four large secondary craters. For these reasons, the large objects hurled as the trailing part of a ray element to great distances from their parent crater are not regarded as blocks of target material, but as fragments of the original meteoritic projectile.

The concept of a 'cometary' impact of underdense material appears to be hopeless in accounting for the survival and ejection to great distance of large projectile fragments. At cometary velocities, typically 20 to 40 km/sec, the impact pressure is so high (~30 mb) and the projectile temperature rise due to shock heating is so great (~10^4 °C), that the comet-head projectile would be vaporized, and therefore incapable of survival and ejection in the form of large solid fragments.

In contradistinction, sizable projectile fragments can be expected to survive a lunar impact of an iron mass coming from an asteroidal orbit. Statistically, objects from such orbits would impact the moon at relatively low velocity, a little over half in the range 3 to 7 km/sec, according to the calculations of *Arnold* [1965]. At 7 km/sec, the peak shock pressure would be about 1 mb [*Gault and Heitowit*, 1963; *Braslau*, 1970], at which pressure the residual temperature rise in iron would be about 650°C [*McQueen et al.*, 1962]. Since this is much less than the 1500°C melting temperature of iron, the fate of such an impacting iron projectile would be mainly fragmentation. Relatively little melting, and negligible vaporization, would occur.

That very large fragments can survive impact and be ejected far from their lunar crater is thus plausible for impacts of asteroidal iron. Meteoritic Fe-Ni inclusions have been found within Australasian tektites, within Ries glass, and within Bosumtwi glass. Consequently, the present model for tektite origin from lunar impact craters, such as Tycho, postulates an original cosmic projectile that was relatively strong and incompressible, probably iron or mainly iron, and that came from a relatively low-velocity orbit of asteroidal type.

It is envisioned that in forming ray ejecta the elevational angular spread ($\Delta\beta$), within the spray of a ray element, and the azimuthal angular spread ($\Delta\delta$), would be roughly the same. At the instant just after the impacting meteorite penetrates below the surface, when it has fragmented and begun to spread out radially, it is clear that the crustal movement cannot be perfectly symmetric. As large blocks of lunar crust begin to fracture, and to move outward, gaps between these crustal blocks will first appear at a discrete number of places around the embryo crater. It is hypothesized that a ray forms when the melange of fragmented meteorite and fused crust under high pressure squirts out through such gaps. During this squirting acceleration, fused crust of density 3 g/cm^3 is more mobile than iron fragments of density 8 g/cm^3, and thus will tend to move around each fragment and spray ahead. This process is suggested as a possible mechanism of forming ray elements. Since, on the average, such fragments would be about as high as wide, $\Delta\beta$ would average about the same as $\Delta\delta$.

Figure 13 illustrates the degree to which a departure from the approximation $\Delta\beta = \Delta\delta$ could affect the Tycho pattern. The earth landing domain for $\Delta\beta = 4°$ ($\beta = 50°$ to $54°$) is seen to be only slightly greater than for $\Delta\beta = 2°$, and not different enough to affect any conclusion. It is to be remembered that $\Delta\delta = 2°$ represents a dispersion broader than the observed width of most lunar rays.

An important feature of the present model is that tektite events can be of more than one type: a 'complete' event if both a large meteorite fragment and most of its associated spray lands on earth; an 'incomplete' event if part of the spray lands while the large fragment misses the earth; a 'truncated' event if the fragment together with only a small portion of spray lands on earth while the major portion of spray misses and travels off into space; and a 'compound' event if two or more fragments with their associated sprays land on earth. Thus a tektite event, if compound, may involve two or more connate craters on earth: if incomplete, no connate crater: if truncated, tektites may land on earth in only a very restricted geographical area near their connate crater.

A number of significant observations about tektites have long required explanation. From the present theory of tektite events, and from the moon-to-earth trajectory computations, explanations can now be given as to why tektites are not spread all over earth, why the moldavites and Ivory Coast tektites are not found all around their connate earth craters, and how it is possible for very restricted tektite distributions, such as the moldavites, to be compatible

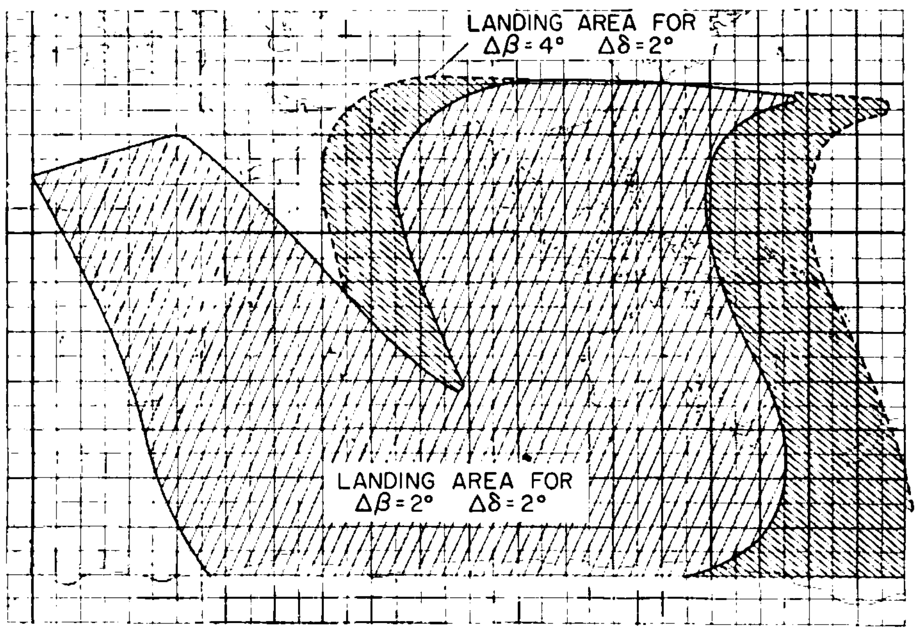


Fig. 13. Areal extension of Tycho landing pattern for $\Delta\beta = 4°$ compared to $\Delta\beta = 2°$.

with a lunar origin. From some recent experiments, an explanation also can be given as to why tektites are mainly acidic and not basic. These and some other explanations pertinent to tektite origin are presented in Appendix 3.

EVIDENCE FROM APOLLO ROCKS RELEVANT TO TEKTITES

Direct information about lunar rocks is limited as of this writing to the samples returned from Apollo 11 and 12 landings, both in maria areas. Since three-fourths of the lunar surface is covered by uplands, as yet unexplored, our present knowledge about lunar rocks must be far from complete. Although the Australasian tektites are concluded to originate from an upland area, whereas these Apollo landings were in maria, several observations pertinent to tektites have emerged from the Apollo data. First, glass in great abundance has been found in the mare soil. Much of this glass is of the size and form of microtektites. Since the mare glass yields unmistakable evidence of impact origin [*Chao et al.*, 1970; *Frederiksson et al.*, 1970; *von Engelhardt et al.*, 1970], we now have direct evidence that impacts have splashed large quantities of glass over the lunar surface. Undoubtedly some glass has splashed beyond the moon's weak gravitation, and hence there can be no reasonable doubt that lunar impact glass has long been here on earth.

Second, one of the samples from Apollo 12, rock 12013, has a composition remarkably similar in most respects to that of some tektites. This rock exhibits a light and a dark component. The light part contains up to 71% SiO_2 [*Morgan and Ehmann*, 1970] and is atypical of the main mass of baaltic rocks returned from the lunar maria. It may be an acidic differentiate of mare-like basalts [*Albee et al.*, 1970; *Laul et al.*, 1970; *Wakita and Schmitt*, 1970*a*]. Although termed 'granitic' [*Albee et al.*, 1970], the abundances of Co, Cr, and Ni in 12013 are strikingly different from earth granites (10 to 100 times higher); water and ferric iron are lacking; and MgO and CaO are comparatively high. Also, K_2O is considerably higher than Na_2O in 12013, whereas the sum $Na_2O + K_2O$ is significantly lower than in typical earth granites. These unusual characteristics are precisely those that long have typified tektites, particularly the HMg type. *O'Keefe* [1970] has pointed out the close similarity in major elements between the preliminary analysis of 12013 and the HMg Javanites of high SG (e.g., JS6, JS7). In Table 2 this comparison is amplified to include minor elements, some more recent analyses of 12013, and an additional tektite analysis (J2). The abundances of 20 out of 23 elements in 12013 fall in the tektite range (all but Ba, Y, Zr); and the abundances of the majority of elements are closely the same as the tektite values.

The over-all composition comparison between 12013 and the tektites is not sufficiently close or complete to constitute in itself strong evidence that tektites come from the moon. Rare earth elements in 12013, for example, exhibit a distinctive trend [*Schnetzler et al.*, 1970; *Hubbard et al.*, 1970] not found in tektites. In particular, Eu shows a pronounced deficiency relative to the other rare earth elements. Lunar anorthosites, in contrast, show a comparably pronounced Eu excess [*Wakita and Schmitt*, 1970*b*]. Thus it appears possible that still other lunar rocks may exhibit the intermediate case of a Eu abundance more like that found in tektites.

Further differences between the chemistry of tektites and that of the lunar rocks returned thus far are found in the oxygen isotopes ratio [*Taylor and Epstein*, 1970] and in the pattern of lead isotopes. Since isotope ratios can be affected by chemical and thermal fractionation processes, they may be different for material that comes from distant upland areas, such as the environs of Tycho, that are far from the mare areas explored thus far. In most lunar samples studied to date, lead is highly radiogenic, although the measurements by *Andersen et al.* [1970] on lunar ilmenite reported lead isotope ratios similar to common terrestrial lead. The Pb isotope pattern reported in several tektites is similar to terrestrial lead, but in at least one tektite is distinctly different [*Starik et al.*, 1962]. Thus far the amount of lead isotope data available on tektites, as well as the variety and number of sites sampled on the moon, are considered too meager to firmly exclude either a terrestrial or a lunar origin for tektites.

The over-all comparison between 12013 and HMg tektites appears sufficiently close to be of some significance. The HMg tektite group is a very distinct and well-defined chemical

TABLE 2. Composition Comparison between Apollo 12 Rock 12013 and Tektites (Oxide in weight per cent, elements in parts per million.)

		Apollo 12 Rock 12013				HMg Tektites	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
SiO_2	61	61	64	71	64.5	65	66
Al_2O_3	12	11	12	11	13	13	13
FeO	10	12	9.6	9.6	8.6	7.9	8.0
MgO	6.0				8.0	6.5	6.8
CaO*	6.3	5.2	6.4	3.9	2.9	3.7	3.3
Na_2O	0.69	1.16	1.36	1.25	0.72	0.77	0.75
K_2O*	2.0	2.0	2.1	3.6	1.34	1.56	1.44
TiO_2	1.2	1.3	0.8	0.8	0.7	0.8	0.8
MnO	0.12	0.16	0.14	0.12	0.18	0.13	0.14
B	15				11	21	21
Ba†	2150	2720	2750	3900	410	345	425
Co	13	35	20	28	56	48	52
Cr‡	1050	1770	1160	980	440	370	400
Ga		6	6	6	3		
La		50	60	59	60		
Ni	105				230	245	250
Pb*	30				<10		
Rb	33	50	49	99		66	
Sr	150				175	171	
Sc	21	28	22	20	16	16	
V	13	80	100	70	80	75	80
Y†	240				32	35	34
Zr†	2200				230	310	275

(1) *Lunar Sample Preliminary Examination Team* [1970].
(2) Fragment 37 + 24 from 12013; *Wakita and Schmitt* [1970], Si from *Morgan and Ehmann* [1970]; Ga and Rb from *Laul et al.* [1970].
(3) Fragment 18 from 12013; ibid.
(4) Fragment 41 from 12013; ibid.
(5) Javanite J86, chemical data from USGS (M. Carron and C. Annell).
(6) Javanite J2, *Chapman and Scheiber* [1969].
(7) Javanite J87, unpublished data of Chapman and Scheiber.
* Apollo 12013 values conform closely with corresponding values for Australasian tektites other than J87, J86, J2.
† Apollo 12013 values not within factor of 2 of other tektites.
‡ Apollo 12013 values within factor of 2 of other tektites.

family exhibiting clearly the classical trends of an igneous differentiation sequence: analyses of this group [*Chapman and Scheiber*, 1969] show that as Si increases, Mg, Ca, Cr, Ni, Co, and Ni/Co decrease; Na, K, Sr/Ca, and Rb/Sr increase; Co-Mg and Co-Fe retain close coherence; Fe/(Fe + Mg) and normative pyroxene and Na/(Na + Ca) in normative plagioclase both increase; and the trends on an FMAlk ternary diagram conform to those of classical crystal fractionation. Yet the HMg tektite chemistry is clearly not that of earth igneous rock chemistry, and it is not that produced by vapor fractionation. For these reasons it has been concluded (ibid.) that this tektite chemistry must represent an extraterrestrial igneous rock chemistry. That the HMg tektite chemistry, which is so distinct from earth igneous rocks, happens to be so close in composition to the first acidic rock returned from the moon is surely an observation that should not pass unnoticed.

The Apollo missions also have revealed data that have been interpreted as constituting a major difficulty for the lunar impact origin of tektites. Thus far only old rocks with differentiation ages 3.3 b.y. or more have been returned from the maria landing sites of Apollo 11 and 12. In contrast, tektites are comparatively young, less than 2.5 b.y. The lunar uplands, it is reasoned, are even older than the maria, and therefore not a likely source of tektites.

Partly because of this apparent difficulty, *O'Keefe* [1970] has abandoned the widely accepted hypothesis of impact origin in favor of the older hypothesis of lunar volcanic origin. The latter, he suggests, circumvents the age difficulty, since the differentiation age of volcanic ejecta could be nearly the same as that of the final paroxysmic eruption which hurled the ejecta into space. However, an alternate explanation not incompatible with the lunar impact hypothesis also appears possible; the ancient uplands, even though comprised mainly of basic material, may contain acidic intrusions of various ages ranging from old to young. The combined physical processes of impact splash, atmosphere entry, and solution decomposition on earth (as explained in Appendix 3) could have resulted in dissolution of the basic glass and selective survival of the acidic glass. Thus the apparent differentiation ages of lunar impact glass which landed and survived on earth of basic material in the moon's crust.

Inasmuch as Surveyor 9 landed near the would be generally younger than the main mass north rim of Tycho and obtained a chemical analysis [*Turkevich et al.*, 1968; *Patterson et al.*, 1970], it is of interest to compare this with the tektite data. Crater ejecta are deposited in an inverted order to the original stratigraphic layering, hence, Surveyor 7 is presumed to have landed on low-velocity ejecta from the last stage of Tycho throw out. Such ejecta could have come from plutonic rock as deep as 10 to 15 km below the original surface [*Gault et al.*, 1968]. Tektites, on the other hand, are thought to originate as high-velocity fused ejecta from a relatively early and more highly shocked stage of the crater excavation process, and thus to represent rock originally from much shallower depths. The Surveyor 7 analysis resembles anorthosite, a rock with SiO_2 (46%) considerably lower, and with CaO (18%) and Al_2O_3 (22%) considerably higher, than in tektites. However, if an extrapolation to lower SiO_2 were made of the compositional trends for the family of HCa australites, which vary systematically over the range of SiO_2 from about 80% down to 66% [*Chapman and Scheiber*, 1969, Figure 9], a composition not greatly different from anorthosite would be obtained. Whether or not a single family of rocks will be found on the moon with such a wide variation in SiO_2, and with chemical characteristics which interlink HCa australites to anorthosite-like rocks, is something yet to be determined from future lunar explorations.

CONCLUDING REMARKS AND IMPLICATIONS FOR SELENOLOGY

Whereas a new theory in physical science can be verified repeatedly by direct evidence from laboratory experiments, any new theory in natural science about an event as ancient as the tektites must necessarily rest on circumstantial evidence. As in a courtroom trial, then, the present circumstantial evidence for the case of lunar tektite origin is summarized as follows: We have the aerodynamic ablation evidence that the Australasian tektites came through the earth's atmosphere as cosmic bullets from the moon; we have the evidence of a 'crater delecti,' Tycho, in the southern hemisphere of the moon within the vicinity where the computer trajectories fix the scene of the crime; we have further the evidence still visible that a shot was fired from Tycho in precisely the right direction; and we have the identifying fingerprint provided by matching the pattern of tektite distribution with the pattern of trajectory trails from Tycho. Moreover, from the Apollo data we have the evidence that glass of the size and form of microtektites has been splashed extensively over the moon; and that the composition of the first acidic rock returned from the moon closely resembles in most respects a tektite composition. In all, this is enough to prosecute for a conviction before the jury of the scientific community.

In view of such evidence, it seems warranted to outline some consequences to selenology that are implied by the conclusions about tektite origin. Inasmuch as tektites are high in silica, and the Australasianites are estimated to comprise as much as 10^8 tons of such glass, the concept of tektite origin by meteoritic impact on the moon clearly implies that:

1. Much glass has been splashed out of impact craters on the moon.

2. The moon has evolved rocks very high in silica, up to at least 85% SiO_2 (89% SiO_2 if Darwin glass is considered as tektite glass). Since it is generally accepted that high-silica rocks on earth are evolved in a late stage of

magnetic differentiation, we are led to the further implication that:

3. The moon's interior has been hot, at least in spots. The Rb-Sr isotope ages of the four known tektite events range from a few hundred million years for Australasian tektites to as much as 2.5×10^{9} years for Ivory Coast tektites. It would be very improbable that a random sample of only four portions of the lunar crust would contain a specimen either of the youngest rock on the moon or of the oldest. Hence:

4. The formation of rocks on the moon (and thus lunar volcanism) must have spanned a very wide range in time, from geologically old to geologically young. The general chemistry of tektites in many respects is so similar to earth rock chemistry that geochemists have commonly preferred an earth origin for the tektites. If geochemists cannot clearly discern tektite chemistry from earth rock chemistry, then we cannot avoid the implication that:

5. The chemical origin of rocks in parts of the lunar crust is somehow closely related to the chemical origin of earth rocks. The principal conclusion of the present investigation—that the Australasian tektites came from the Rosse ray of Tycho—leads to two additional implications:

6. Tycho was formed at the same time as the Australasian tektites, about 700,000 years ago according to present age data.

7. The lunar upland areas near Tycho have evolved a number of different varieties of acidic igneous rock ranging widely in chemical composition.

Some, but not all, of these selenological implications have been confirmed by Apollo landings. As yet none have been demolished. Implication 1 has been decisively confirmed by the discovery in the lunar regolith of embarassingly large quantities of glass of microtektite size and shape. 'There are glass beads in every crater you come to and look in,' Apollo Astronaut Bean commented. Implication 2 has not yet been positively confirmed; but the discovery of glassy mesostasis containing as much as 78% SiO_2 within the interstices between crystals of the Apollo 11 basalts [*Roedder and Weiblen*, 1970; *Kushiro et al.*, 1970; *Keil et al.*, 1970; *Agrell et al.*, 1970; *Anderson et al.*, 1970] has led to the anticipation that granite-like rocks at least this high in silica will be found somewhere on the moon. Implication 3, long antithetical to the 'cold moon' idea, is consistent with Apollo 11 and Apollo 12 findings: the upwelling of basaltic magma of such vast extent as the maria, and the clear differentiation sequence of the Apollo 12 rocks [*Lunar Sample Preliminary Examination Team*, 1970] are compatible with this implication. Implication 4, though, has not yet been confirmed, inasmuch as only geologically old rocks have been identified thus far in the Apollo samples. Since basalt, anorthosite, and a 'granite,' all rock types common on earth, have already been returned by the astronauts, implication 5 is considered to be reasonably corroborated by the Apollo data. Implications 6 and 7, however, remain to be tested by future landings in the lunar uplands.

Appendix 1. Previous Attempts to Outline the Distribution Pattern

It may be of interest to explain why previous attempts to define a geometric pattern within the strewnfield of Australasian tektites have led to patterns different from that constructed herein. From early measurements of the specific gravity of australites mainly from the three concentration centers of Victoria (2.41+ mode), Charlotte Waters (2.43+ mode), and Kalgoorlie (2.45+ mode), it was thought that there was a simple gradient pattern of silica decreasing from east to west across Australia [*Summers*, 1909; *Baker and Forster*, 1943]. But our more complete data on SG from more than thirty different australite localities now show that the population of highest SG is not in western Australia but is near the eastern coast (Uralla, 2.46+ mode), and the australite populations of lowest SG are not in eastern Australia but in central Australia (2.38+ mode). Thus these early SG data were simply inadequate in scope. A different pattern was suggested by *Beyer* [1933], who constructed from 25 chemical analyses then available a 'great-circle band' running northwest from Australia across Southeast Asia. His data also were inadequate in number. Still a different approach was taken by *Cohen* [1962]. Mainly on the basis of the Ni abundance at ten localities in the northern part of the strewnfield, he two-lobe distribution pattern emanating hailand, one lobe low in Ni (less than 32 extending eastward to the Philippines, e lobe high in Ni (over 125 ppm) ex-g southward to Java. But our subsequent rements from about 20 times as many lo-as were available to Cohen (including localities used by Cohen) outline a dif-pattern (Figure 3). A number of locali-ith Ni over 125 ppm, for example, have een found within his 'low Ni' lobe (e.g., uin, 325 ppm; South China Sea, 205 Plateau Van Hoa, 250 ppm; Buon r, 295 ppm; Kouang Tcheou Wan, 180 From a study of tektite internal struc-principally lechatelierite abundance and *Barnes* [1964] suggested that a concentric n exists in Southeast Asia, elongate in ortheast direction and centered around nd and Laos. He studied twelve locali-this area, but his limited data can also erpreted as a northeast streak pattern—tern that would be compatible with that ed from the more extensive chemical data present study. In essence, the raw data n these four previous studies do not con-with those of the present investigation: trewnfield distribution pattern is simply omplex for even its principal features to been discerned from the relatively meager previously available.

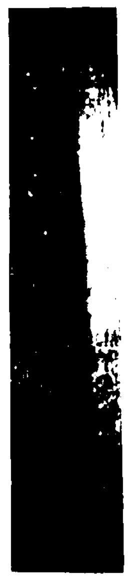
ently, from a study of the abundance rn of australites, *McColl and Williams*] observed that two principal lines of dis-tion could be discerned: one stretching Port Campbell NW to Charlotte Waters, one from the Nullarbor Plain NNW to Wilson. Both of these lines are compati-ith the distribution pattern deduced herein the pattern of chemical variations.

ENDIX 2. EXAMPLES OF THE COMBINED SE OF SPECIFIC GRAVITY AND CHEMICAL DATA

e data from SG polygons and chemical ses were used in delineating fine structure g all but the uncommon or rare chemical s. For example, the SG polygons at Ban Lai in North Vietnam, at Pahang in Ma-and at Lumpoon in West Thailand are ally quite similar, each exhibiting a prom-mode at 2.43+ of the type illustrated by Pahang in Figure 4c. The Ban Tre Lai specimens are all low Ni (four analyses) and include some HCu.B types, whereas the Pahang specimens are all medium-high Ni (three analyses). Hence, this particular pair of localities is not taken as a match. On the other hand, tektites in Malaya are of the same chemical type as those in West Thailand ('Chiang-Rai' type, CaO/MgO greater than or equal to unity, with medium-high Ni); their SG polygons are also of the same homogeneous type; and individual specimens from Batu Gajah in Malaya, and from Ban Mae Jong in West Thailand are found to chemically match (Table 1, match 8). This pair of localities in Malaya and West Thailand, therefore, is taken as a match. As another illustrative example, a specimen from Serpentine Lakes, South Australia, nearly matches the chemistry of a West Thailand specimen [*Chapman and Scheiber*, 1969, analyses 51 and 56]. The SG polygon at Serpentine Lakes, however, is of the heterogeneous type, without a prominent mode (Figure 4*b*), and with high SG specimens (above 2.46); whereas those in West Thailand are of the homogeneous 'spike' type with a very prominent mode, and without high SG specimens (Figure 4*c*). Hence Serpentine Lakes and West Thailand are not taken as matching localities. As a final example, chemical matches with Dalat tektites are found in North Cambodia and also in South China (Kouang Tcheou Wan). The SG polygons in North Cambodia, however, are relatively heterogeneous, containing high SG specimens (above 2.46), whereas the SG polygon for Dalat and South China cuts off at 2.45. The Dalat polygon has the same mode and is closely similar to the higher SG component polygon of the bi-modal polygon for Kouang Tcheou Wan; and chemical matches exist between these two localities (Table 1, match 3); hence Dalat and Kouang Tcheou Wan are taken as a match.

APPENDIX 3. POSSIBLE EXPLANATIONS OF SOME SIGNIFICANT OBSERVATIONS ABOUT TEKTITES

Why tektites are glass. Crater ejecta shock-accelerated to a low velocity would comprise mainly warmed breccia; but ejecta shock-accelerated to lunar escape velocity would comprise thoroughly fused material. This follows from the Rankine-Hugoniot law for energy



partition in a strong shock wave: $\Delta E = V_p^2/2$, where E is the internal energy per unit mass, and V_p is the particle velocity reached by shock acceleration. Shock acceleration to $V_p = 2.6$ km/sec, the most probable lunar ejecta velocity for hitting the earth, would impart $(2.6 \times 10^5)^2/2 = 3.4 \times 10^{10}$ erg/g of internal energy. After ejection into space, and adiabatic unloading of pressure, about half to two-thirds of this energy would remain as internal energy, corresponding roughly to 500 cal/g, or to temperatures of about 1800°C. The simultaneous combination of high temperature with very high shock pressure (hundreds of kilobars) is believed to be sufficient to thoroughly fuse silicates. We can thus explain why tektites are glass; why unfused mineral grains are rare in tektites; and why gobs of partially fused tektite material are not found on earth. An impact creates much more brecciated and partially fused material than glass; but such material, low in velocity, would remain near its source on the moon.

Why tektites are not spread all over the earth. The areal spread on earth of tektites from a single event is confined to only a portion of the globe by the pronounced effect of earth gravitational focusing. This can be illustrated by the moon-to-earth trajectories for the ejecta from the Rosse ray of Tycho. Shown to scale in Figure 14 are the positions of a cluster of 16 particles at three different times of 1, 2, and 2.9 days after leaving Tycho. Two views are depicted, one normal and one parallel to the ecliptic plane; the moon position is shown only at the instant of lunar impact. These 16 particles leave the moon with an azimuthal and an elevational velocity dispersion equal to 3% of the mean cluster ejection velocity (a dispersion equivalent to $\Delta\delta = 2°$ in azimuth, and $\Delta\beta = 2°$ in elevation). The longitudinal velocity dispersion, 2.55 to 2.73 km/sec, is 8% of the mean velocity, corresponding to several times the transverse dispersion. This is roughly the elongate proportions of typical 'ray elements' visible on the moon. Velocities greater than 2.73, or less than 2.55 km/sec, would miss the earth. It is seen that after one day the cluster has spread over dimensions several times the earth's diameter; and at 2.9 days, when the leading particle hits earth, the remaining particles are strewn in space over a third of the distance to the moon, stretching about 150,000 km along, and about 50,000 km transverse to, the mean trajectory path. Yet, at 3.5 days, all this highly strung-out cluster has landed on earth confined to a geographic spread of only 13,000 km in longitude by 9,000 km in latitude! Some scientists have disregarded the idea of lunar tektite origin on the unfounded belief that impact ejecta from the moon would spread all over earth. Such 'objections' overlook, among other things, this powerful effect of earth gravitational focusing. The earth's rotation, it should be noted, also happens to be in such a direction as to *compress* the geographic longitude spread of the ejecta relative to what it would be without rotation.

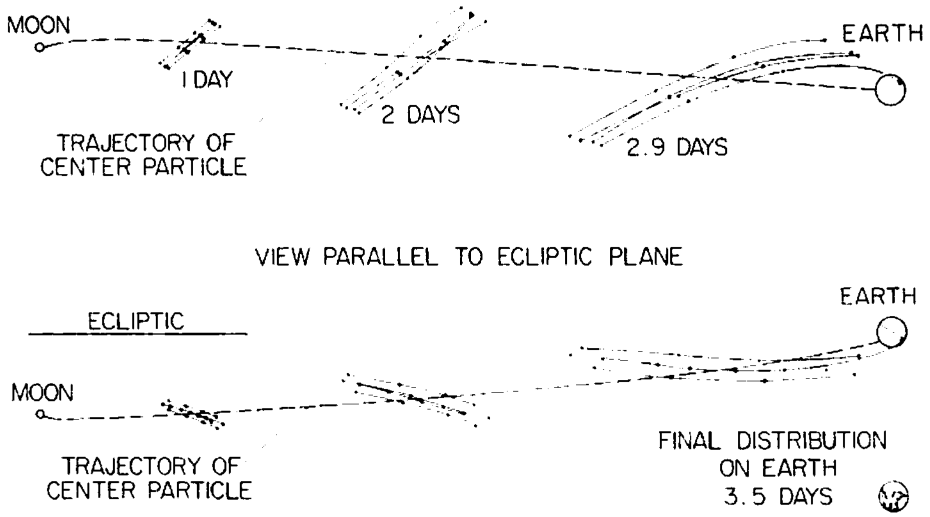


Fig. 14. Scale diagram of cluster position and spread in space during travel from Tycho to earth.

The major fraction of lunar crater ejecta that escapes the moon must miss the earth. It has been suggested that this fraction would later return and that glass in the recognizable form of tektites should be spread randomly over earth. Such returns, however, require on the average the order of 10^6 years or more before a probable encounter with earth; whereas the mean lifetime in space before destruction of tektite glass by meteoric bombardment, as *Gault and Wedekind* [1969] estimate, is several orders of magnitude less. The 'returns,' therefore, would not be tektites, but tektite dust comprising only a small fraction of the total meteoric dust that continually enters the earth's atmosphere. Some of the small particles may also be destroyed by the mechanism of 'rotational bursting' described by *Paddack* [1969].

Why moldavites and Ivory Coast tektites are not found all around their connate earth craters. An evident consequence of the present model for tektite events is that, when a ray element comprising spray and a trailing large fragment is hurled to earth, the tektite spray streams out mainly ahead of the fragment, and thus lands mainly on one side only of the connate crater—not uniformly all around it. This provides an explanation of why the moldavites are found on one side only of Ries crater, and why the Ivory Coast tektites and microtektites are found on one side only of Bosumtwi crater. Within the scope of this model, glass of tektite composition could be found right up to, and even in the immediate vicinity of, a connate crater.

How a very restricted tektite distribution, such as the moldavites, can be compatible with a lunar origin. As was noted earlier, the present model includes the possibility of a tektite event that is truncated. Few ray elements would travel dead-center toward earth. In a truncated event, most of the spray can miss the earth, in which case the small fraction that lands as tektites would land only in a restricted area near their connate crater. Also, a 2° spread of spray ($\Delta\beta = \Delta\delta = 2°$) like that used in most of the illustrations herein is considerably larger than for many ray elements observed on the moon. Some show only about 1/2° spread; these, if truncated, would land on earth in an area greatly confined both in length and breadth. Such circumstances, together with the processes of geological obscuration that have acted over the 15-million-year period since the moldavites fell, provide a possible explanation of the very restricted distribution known at present for this tektite group.

How it is possible for the australites to be restricted mainly to the southern part of the continent. It has long been known that few, if any, australites are found north of about 23°S latitude. Such a 'cut off' in latitude could result if the Australasian event were compound, and if many of the australites were associated with a connate crater that formed somewhere in the north of Australia. It is of interest, perhaps, to speculate on an earth crater that might be connate with the australites. Wolf Creek crater was formed by an iron meteorite, and is situated in northern Australia at a locality precisely aligned with the LSG–HCa streak. The HCa australites are not found elsewhere in the Australasian strewnfield. Unlike other meteoritic craters, the iron shale masses found around Wolf Creek commonly resemble teardrops, pears, disks, bananas [*McCall*, 1965], shapes typical of deformation and formation of iron in a plastic or highly viscous state. A meteoritic fragment of such size as that which formed Wolf Creek crater would cool little in a 3-day journey from moon to earth. Such a fragment, first shock heated throughout to the order of 650° during a lunar impact, would be shock heated a second time upon striking earth; and this time heated to temperatures at which iron softens and is readily deformed or extruded. Hence, if Wolf Creek crater is connate to the Australasian tektites, we would have an explanation for the curious shapes of iron shale masses found around this crater.

In Figure 15 the trajectory landing pattern is illustrated for a hypothetical compound event from Tycho comprising two ray elements: a major one, with $\Delta\beta = \Delta\delta = 1°$, and a minor one with $\Delta\beta = \Delta\delta = 0.8°$. The smaller projectile fragment associated with this minor ray element would leave Tycho at $V_E = 2.572$ km/sec, $\beta = 50.0°$, and $\delta = 17.5°$ in order to impact earth at Wolf Creek crater. These launch angles for β and δ are within 1° of those for the major fragment which could either have impacted somewhere in the Pacific Ocean or have missed the earth. Such a compound event

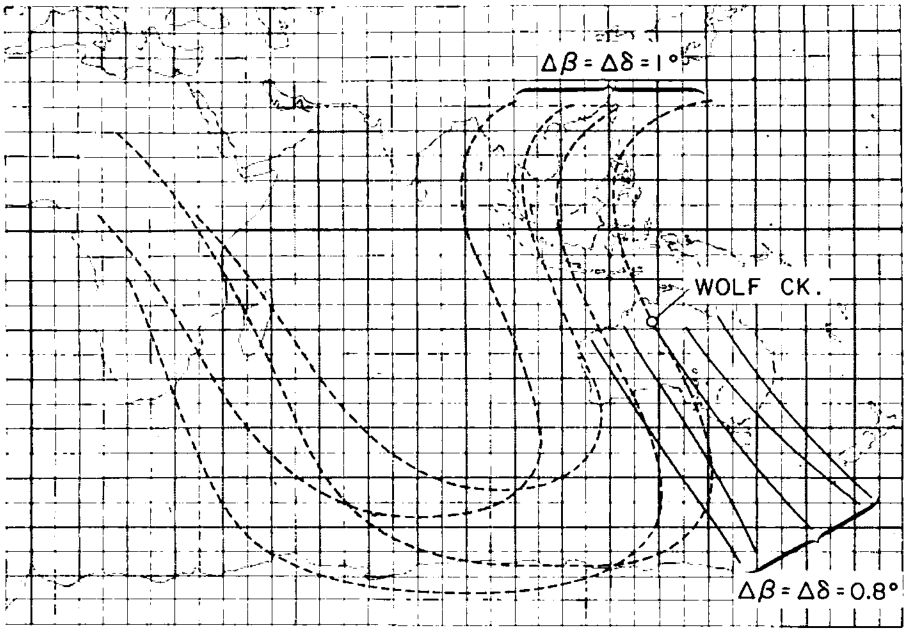


Fig. 15. Example of hypothetical compound event from Tycho comprising two ray elements: Projectile fragment for major element ($\Delta\beta = \Delta\delta = 1°$) lands either in Pacific or misses earth; projectile fragment for minor element ($\Delta\beta = \Delta\delta = 0.8°$) lands at Wolf Creek, Australia.

provides a possible, but as yet unsubstantiated, explanation for the observed latitude cut off of the australites. The age of Wolf Creek crater has not yet been determined; but its general appearance is such as to warrant investigation as a possible crater connate to the australites.

The trajectory trails in Figure 15 also illustrate that a 1° spray dispersion ($\Delta\beta = \Delta\delta = 1°$), which is representative of many lunar ray elements, is essentially adequate to explain the Australasian distribution pattern. The fact that a 2° spray dispersion was used for most illustrations herein is not critical to the principal conclusion that the Tycho ejecta pattern conforms to the tektite distribution pattern.

If the Australasian event were compound, it is also dynamically possible for one of the fragments to land in Africa near the Ivory Coast tektites. Present age data, however, apparently exclude such an association [*Gentner et al.*, 1970].

Why tektite shape variations are somewhat restricted. The law of energy equipartition for shock acceleration, combined with the relatively narrow range in lunar ejection velocity V_E that sends material to earth, provides a semiquantitative explanation of the most common variations in tektite shape. The Tycho ejecta that spreads from southern Australia to Southeast Asia, for example, represents V_E between 2.62 and 2.55 km/sec. The corresponding internal energies at ejection would vary by the factor $(2.62/2.55)^2 = 1.06$. This, in turn, corresponds to a temperature variation of about 130°C, which, for a given tektite composition, corresponds to a variation in viscosity by a factor of about 4. Since Australasianites commonly vary in SiO_2 from 70 to 80%, this introduces at the temperatures of formation additional variations in viscosity by another factor of 10. Variations in porosity of the pre-impact rock could introduce still further variations in viscosity for a given V_E. An over-all variation in viscosity by a factor of 40 is compatible with the observed variation in shapes of most tektites, such as from mainly small round forms in the Nullarbor Plains of Australia where SiO_2 averages about 70%, to mainly teardrops and more irregular shapes in Southeast Asia where SiO_2 averages about 75%. Experiments with glass ejection at various temperatures have shown that a variation in viscosity of formation by a factor of 44 [*Chapman*, 1964, Figure 12] produces shape and size variations from mainly round forms of small size to mainly teardrops and irregular forms of much larger size. Thus the Tycho trajectory calculations and corresponding energies provide reasonable explanation of the principal variations in Australasian tektite shape. Most of the ejecta that reaches earth from other lunar craters, such as those that produced the moldavites and the North American tektites, also would have left the moon in nearly the same velocity range (2.55 to 2.8 km/sec). Hence we also have an explanation of the striking conformity observed between the shapes of moldavites and of Southeast Asian tektites, as well as the general similarity in shapes between bediasites, Ivory Coast tektites, and certain Australasianites.

Why land tektites are acidic and not basic. Three factors are extremely selective for the survival of high-silica materials in a tektite event, and, hence, highly relevant to any deductions about the relative proportions of basic and acidic rock that may have existed at the crater impact site. The processes of impact splash, of atmosphere entry, and of terrestrial decomposition each act to selectively destroy basic glass exposed to the same severe physical environment that tektites have survived. First, because of its lower viscosity, basic glass splashed from an impact crater would solidify into smaller primary forms than acidic glass exposed to the same temperatures and forces of disruption. This has been demonstrated by experiments [*Chapman*, 1964] in which glasses of various viscosity were ejected from a pressurized tube, and recovered as splash forms—the lower the viscosity, the smaller the size recovered. On the basis of these experiments, it is to be expected that the same disruption process that produced tektite splash forms typically of centimeter size and rarely of 10-cm size, would produce basic glass forms typically of several mm size, and rarely of several cm size. Second, these smaller splash forms of basic glass, again because of their lower viscosity, would not survive the atmosphere entry that acidic tektites have survived. This has been proven by aerodynamic ablation experiments in which two spheres, one of tektite glass and one of basalt glass were placed in the same arc-jet stream. The amount of aerodynamic heating that turned a 2-cm tektite sphere into a typical australite button melted all but a small fraction of the sphere of basalt glass. This experiment is illustrated in Figure 16. Similar experiments also showed that the aerodynamic heating that turned a 1-cm tektite sphere into a button completely melted a 1-cm sphere of basalt glass. Hence, basic glass of several millimeters to 1 cm size would land on the ground only as a glass mist of ablation droplets a fraction of a millimeter in size. Third, small ablation droplets of basic glass

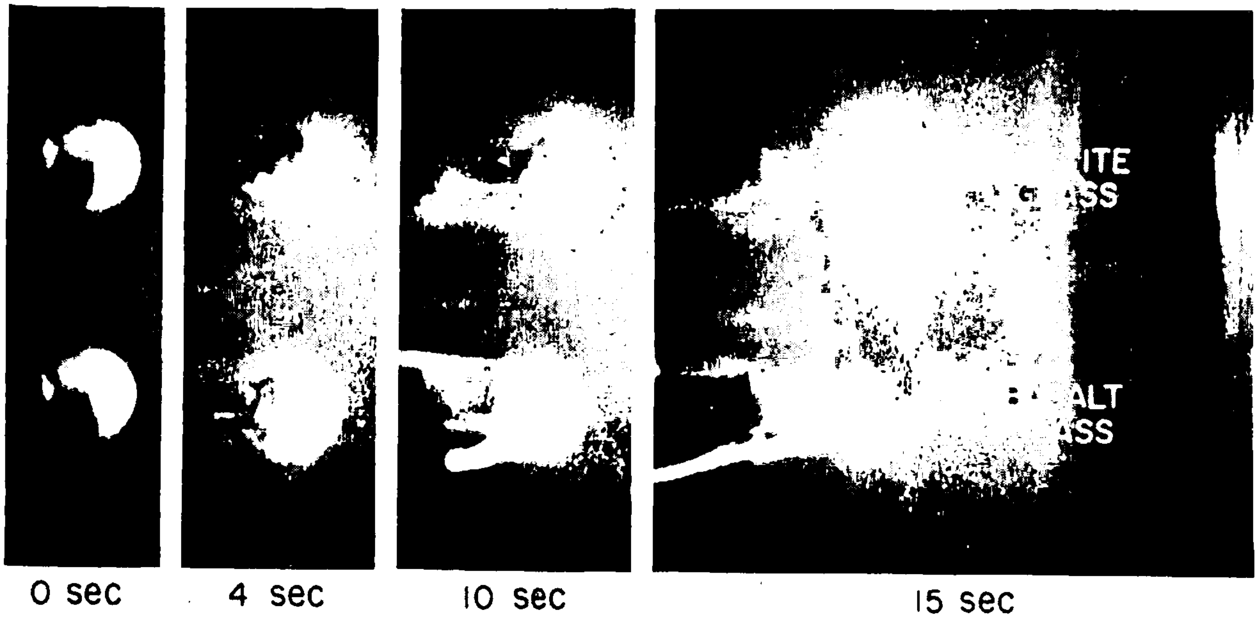


Fig. 16. Photographs taken during aerodynamic ablation experiment illustrate the difference between the ablation of tektite glass (*top*) and basalt glass (*bottom*). Arc-jet stream flows from right to left.

would not survive decomposition by ground waters. This has been established by some recent unpublished experiments of Mr. Frank Centolanzi who found that fresh water decomposes basaltic glass at ten times the rate of tektite glass. His measurements correspond to a decomposition rate at room temperature of 2 mm/m.y. for tektite glass, and approximately 2 cm/m.y. for basalt glass. Hence, basalt glass that is wet only a few days per year would decompose a few tenths of a millimeter in 700,000 years, enough to dissolve the ablation droplet remains of basalt glass. Because of these three powerful screening processes for selective survival of acidic glass, it follows that the Australasian tektite shower might have been accompanied by more basic than acidic glass, and we would have no way of knowing that today from observations on land.

In deep-sea cores, however, some basic microtektites have survived; and this is indeed consistent with Centolanzi's experiments. He observed that, whereas tektites and basalt glass lose weight by decomposing in fresh water, they do not in salt water. In fact, they gain a little weight in salt water. Some other glasses of different chemistry decompose in salt water. Depending upon the glass chemistry, therefore, and perhaps upon the chemistry of the sediment in which the glass is immersed, small droplets of basic glass (microtektites) in deep-sea sediments may or may not survive decomposition for 700,000 years. Thus, only a lower limit can be placed on the fraction of basic glass that originally accompanied the Australasian tektites; it was at least as large as the fraction recoverable today among microtektites, and possibly much larger.

Acknowledgments. I am singularly indebted to H. Julian Allen, a former colleague in aerodynamics and warm personal friend, who told me, two years before I could see how it possibly could be done, that if I were really any good as an aerodynamicist, I should be able to figure out from which crater and which ray the tektites came. I also thank Frank J. Centolanzi, Leroy C. Scheiber, and Norman B. Zimmerman, who have assisted in many phases of this research since its inception in 1960.

References

Agrell, S. O., J. H. Scoon, I. D. Muir, J. V. P. Long, J. D. C. McConnell, and A. Peckett, Mineralogy and petrology of some lunar samples, *Science, 167*, 583–586, 1970.

Albee, A. L., D. Burnett, A. Chodos, E. Haines, J. Huneke, D. Papanastassiou, F. Podosek, G. Russ, III, and G. Wasserburg, Mineralogic and isotopic investigations on lunar rock 12013, *Earth Planet. Sci. Lett., 9*, 137–163, 1970.

Andersen, C. A., J. R. Hinthorne, and K. Fredriksson, Ion microprobe analysis of lunar material from Apollo 11, *Proc. Apollo 11 Lunar Science Conference, vol. 1*, 159–167, Pergamon, New York, 1970.

Anderson, A. T., Jr., A. V. Crewe, J. R. Goldsmith, P. B. Moore, J. C. Newton, E. J. Olsen, J. V. Smith, and P. J. Wyllie, Petrologic history of moon suggested by petrography, mineralogy and crystallography, *Science, 167*, 587–590, 1970.

Arnold, J. R., The origin of meteorites as small bodies, 2, The model, *Astrophys. J., 141*, 1536–1547, 1965.

Baker, G., and H. C. Forster, The specific gravity relationships of australites, *Amer. J. Sci., 241*, 377–406, 1943.

Barnes, V. E., Tektite strewn-fields, in *Tektites*, edited by J. A. O'Keefe, chap. 2, University of Chicago Press, Chicago, Ill., 1963*a*.

Barnes, V. E., Detrital mineral grains in tektites, *Science, 142*, 1651–1652, 1963*b*.

Barnes, V. E., Variation of petrographic and chemical characteristics of indochinite tektites within their strewnfield, *Geochim. Cosmochim. Acta, 28*, 893–913, 1964.

Beyer, H. O., The chemistry of tektites, and notes on their physical grouping, in *Phillippine Tektites*, vol. 1, part 1, pp. 59–86, 1933. (University of the Philippine Publications, 1961–1962).

Billerbeck-Gentz, F. Unterbrechungserscheinungen am mondstrahl Tycho-Polybius-Fracastor-Rosse, *Astron. Nachr. 274*, 140, 1943.

Braslau, D., Partitioning of energy in hypervelocity impact against loose sand targets, *J. Geophys. Res., 75*, 3987–3999, 1970.

Cassidy, W. A., B. Glass, and B. C. Heezen, Physical and chemical properties of Australasian microtektites, *J. Geophys. Res., 74*, 1008–1025, 1969.

Chao, E. C. T., E. J. Dwornik, and J. Littler, New data on the nickel-iron spherules from Southeast Asian tektites and their implications, *Geochim. Cosmochim. Acta, 28*, 971–980, 1964.

Chao, E. C. T., O. B. James, J. A. Minkin, J. A. Boreman, E. D. Jackson, and C. D. Raleigh, Petrology of unshocked crystalline rocks and shock effects in lunar rocks and minerals, *Science, 167*, 644–647, 1970.

Chapman, D. R., On the unity and origin of the Australasian tektites, *Geochim. Cosmochim. Acta, 28*, 841–880, 1964.

Chapman, D. R., A theory of tektite events and possible lunar crater of Australasian tektite origin, *Eos Trans. AGU, 49*(1), 244, 1968.

Chapman, D. R., and D. E. Gault, Critique of

Cometary impact and the origin of tektites,' J. *Geophys. Res.*, *72*, 2695–2699, 1967.
Chapman, D. R., and H. K. Larson, On the lunar origin of tektites, *J. Geophys. Res.*, *68*, 4305–4358, 1963.
Chapman, D. R., and L. C. Scheiber, Chemical investigation of Australasian tektites, *J. Geophys. Res.*, *74*, 6737–6776, 1969.
Chapman, D. R., H. K. Larson, and L. C. Scheiber, Population polygons of tektite specific gravity for various localities in Australasia, *Geochim Cosmochim. Acta*, *28*, 821–839, 1964.
Compston, W., and D. R. Chapman, Sr isotope patterns within the Southeast Australasian strewn-field, *Geochim. Cosmochim. Acta*, *33*, 1023–1036, 1969.
Cohen, A. J., Asteroid-impact hypothesis of tektite origin, 3, The Southeast Asian strewn-fields, *Space Res.*, *3*, 950–973, 1962.
Darwin, C., *Geological Observations on the Volcanic Islands and Parts of South America Visited during the Voyage of H.M.S. Beagle*, pp. 44–45, 1844. (Republished by Appleton, New York, 1891.)
Fleischer, R. L., P. B. Price, and R. M. Walker, On the simultaneous origin of tektites and other natural glasses, *Geochim. Cosmochim. Acta*, *29*, 161–166, 1965.
Fredriksson, K., J. Nelen, W. G. Melson, E. P. Henderson, and C. A. Anderson, Lunar glasses and micro-breccias: Properties and origin, *Science*, *167*, 664–666, 1970.
Gault, D. E., and E. D. Heitowit, The partition of energy for hypervelocity impact craters formed in rock, *Proceedings of Sixth Hypervelocity Impact Symposium, Cleveland, Ohio*, sponsored by the U.S. Army, vol. 2, 419–456, 1963.
Gault, D. E., E. M. Shoemaker, and H. J. Moore, Spray ejected from the lunar surface, *NASA Tech. Note D-1767*, 1962.
Gault, D. E., and J. A. Wedekind, The destruction of tektites by micrometeoroid impact, *J. Geophys. Res.*, *74*, 6780–6794, 1969.
Gault, D. E., J. B. Adams, R. J. Collins, G. P. Kuiper, H. Masursky, J. A. O'Keefe, R. A. Phinney, and E. M. Shoemaker, Lunar theory and processes, *Jet Propulsion Laboratory Tech. Rep. 32-1264*, chap. 9, 267–313, 1968.
Gentner, W., and J. Zähringer, Das Kalium-Argon Alter von Tektiten, *Z. Naturforsch.*, *15a*(2), 93–99, 1960.
Gentner, W., H. J. Lippolt, and O. Muller, Das Kalium-argon-alter des Bosumtwi-Kraters in Ghana und die chemische Beschaffenheit seiner Glaser, *Z. Naturforsch.*, *19a*, 150–153, 1964.
Gentner, W., B. Kleinmann, and G. A. Wagner, New K-Ar and fission track ages of impact glasses and tektites, *Earth Planet. Sci. Lett.*, *2*, 83–86, 1967.
Gentner, W., B. P. Glass, D. Storzer, and G. A. Wagner, Fission track ages and ages of deposition of deep-sea microtektites, *Science*, *168*, 359–361, 1970.
Glass, B., Microtektites in deep-sea sediments, *Nature*, *214*, 372–374, 1967.
Glass, B. P., Glassy objects (microtektites?) from deep-sea sediments near the Ivory Coast, *Science*, *161*, 891–893, 1968.
Glass, B. P., Chemical composition of Ivory Coast microtektites, *Geochim. Cosmochim. Acta*, *33*, 1135–1147, 1969.
Glass, B. P., Chromite and zircon crystals in a Muong Nong tektite, *Eos Trans. AGU*, *51*(4), 341, 1970.
Hubbard, N. J., P. W. Gast, and H. W. Wiesmann, Rare earth, alkaline and alkaline metal and ^{87}Sr/^{86}Sr data for subsamples of lunar sample 12013, *Earth Planet. Sci. Lett.*, *9*, 181–184, 1970.
Keil, K., M. Prinz, and T. E. Bunch, Mineral chemistry of lunar samples, *Science*, *167*, 597–599, 1970.
Kuiper, G. P., Interpretation of Ranger VII records, *Jet Propulsion Laboratory Tech. Rep. 32-700*, 9–73, 1965.
Kushiro, I., Y. Nakamura, H. Haramura, and S. Skimoto, Crystallization of some lunar mafic magmas and generation of rhyolitic liquid, *Science*, *167*, 610–612, 1970.
Laul, J. C., R. Keays, R. Ganapathy, and E. Anders, Abundance of 14 trace elements in lunar rock 12013, *Earth Planet. Sci. Lett.*, *9*, 211–215, 1970.
Lin, S. C., Cometary impact and the origin of tektites, *J. Geophys. Res.*, *71*, 2427–2437, 1966.
Lunar Sample Preliminary Examination Team, Preliminary examination of lunar samples from Apollo 12, *Science*, *167*, 1325–1339, 1970.
McCall, G. J. H., Possible meteorite craters: Wolf Creek, Australia, and analogs, *Ann. N. Y. Acad. Sci.*, *123*, art. 2, 970–998, 1965.
McColl, D. H., and G. E. Williams, Australite distribution pattern in southern Central Australia, *Nature*, *226*, 154–155, 1970.
McQueen, R. G., E. Zukas, and S. Marsh, Residual temperatures of shock-loaded iron, *ASTM Special Publ. 336*, 306–316, 1962.
Morgan, J. W., and W. D. Ehmann, Lunar rock 12013, 10; O, Si, and Fe abundances, *Earth Planet. Sci. Lett.*, *9*, 164–168, 1970.
O'Keefe, J. A., Tektite glass in Apollo 12 sample, *Science*, *168*, 1209–1210, 1970.
Paddack, S. J., Rotational bursting of small celestial bodies: Effects of radiation pressure, *J. Geophys. Res.*, *74*, 4379–4381, 1969.
Patterson, J. H., A. L. Turkevich, E. J. Franzgrote, T. E. Economou, and K. P. Sowinski, Chemical composition of the lunar surface in a terra region near the crater Tycho, *Science*, *168*, 825–828, 1970.
Pickering, W. H., An investigation of the systems of bright streaks visible upon the full moon, *Astron. Nachr.*, *130*(3111), 225–228, 1892.
Reynolds, J. H., Rare gases in tektites, *Geochim. Cosmochim. Acta*, *20*, 101–114, 1960.
Roedder, E., and P. W. Weiblen, Silicate liquid immiscibility in lunar magmas, evidenced by

melt inclusions in lunar rocks, *Science, 167,* 641–644, 1970.

Schieber, L. C., Comparison of tektite polygons of bulk specific gravity, true material specific gravity, and refractive index, *J. Geophys. Res., 75,* 7513–7515, 1970.

Schnetzler, C. C., J. A. Philpotts, and M. L. Bottino, Li, K, Rb, Sr, Ba and rare-earth concentrations and Rb-Sr age of lunar rock 12013, *Earth Planet. Sci. Lett., 9,* 185–192, 1970.

Starik, I. Y., E. V. Subotovich, M. M. Shats, and S. M. Grashchenko, On the question of the origin of tektites, NASA TTF-113, 1962. Translation of K voprosu o proiskhozhdenii tektitov, *Meteoritika, 22,* 97–102, 1962.

Summers, H. S., Obsidianities: Their origin from a chemical standpoint, *Proc. Roy. Soc. Victoria, 21*(2), 423–443, 1909.

Taylor, H. P., and S. Epstein, Correlations between O^{18}/O^{16} ratios and chemical compositions of tektites, *J. Geophys. Res., 74,* 6834–6844, 1969.

Taylor, H. P., and S. Epstein, Oxygen and silicon isotope ratios of lunar rock 12013, *Earth Planet. Sci. Lett., 9,* 208–210, 1970.

Turkevich, A. L., E. J. Franzgrote, and J. H. Patterson, Chemical analysis of the moon at the Surveyor 7 landing site: Preliminary results, *Science, 162,* 117–118, 1968.

Viste, E., and E. Anders, Cosmic-ray exposure history of tektites, *J. Geophys. Res., 67,* 2913–2919, 1962.

von Engelhardt, W., J. Arndt, W. F. Muller, and D. Stoffer, Shock metamorphism in lunar samples, *Science, 167,* 669–670, 1970.

von Koenigswald, G. H. R., Tektite studies, The origin of tektites, *Proc. Kon. Ned. Akad. Wetensch., Ser. B, 70,* 104–112, 1967.

Walter, L. S., Coesite discovered in tektites, *Science, 147,* 1029–1032, 1965.

Wakita, H., and R. A. Schmitt, Elemental abundances in seven fragments from lunar rock 12013, *Earth Planet. Sci. Lett., 9,* 169–176, 1970*a*.

Wakita, H., and R. A. Schmitt, Lunar anorthosites: Rare-earth and other elemental abundances, *Science, 170,* 969–974, 1970*b*.

Whitaker, E. A., Further observations on the Ranger VII records, *Jet Propulsion Laboratory Tech. Rep. 32-700,* 149–154, 1965.

(Received November 2, 1970.)